Applied Physics Series

PHOTOGRAPHY AS A SCIENTIFIC IMPLEMENT

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A Collective Work by

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NOTE BY THE PUBLISHERS

It is probably not too much to say that the most definite advances in observational scientific investigation made in recent years have proceeded from the application of photography. The convenience, rapidity, and exactness of photographic methods have established photography firmly as a necessary aid to research in, for example, astronomy, surveying, aeronautical observation, microscopy, metallurgy, engineering, and physics. The methods of technique developed by experts in these and other spheres of research are, not uncommonly, hidden in the *Transactions* of the learned societies, or in publications devoted to a special branch; it has therefore seemed desirable to gather into one volume the whole results achieved, and thus make available to workers in any particular branch those methods developed in other branches, but frequently capable of general application and usefulness.

The several branches dealt with are treated in separate chapters, each by an expert in the particular subject. As the various experts have worked together with a common aim, it is hoped that virtual uniformity of treatment has been secured.

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CHAPTER I
The History of Photography

It is difficult to give a date to the beginnings of photography. Perhaps the " discovery " was made by the man who first noticed that the skin is tanned by the summer sun. The sun's rays affect nearly every known chemical to some extent. One of the problems of the dye industry, for instance, is to find coloured substances which are not affected by light.

It is not surprising that the invention of the camera cannot be accredited to any one person. The word *camera* suggests a room or chamber, and even if we did not know the history of the camera obscura, we should expect to find that the first cameras were in reality rooms.

In the early days of amateur photography, Mr. Kibble, who presented the large glass conservatory, known as " The Kibble ", to the Botanic Gardens, Glasgow, had made for himself a very large camera, not unlike a removal van, which was mounted on a lorry. The photographic artist remained inside the camera during the taking of a photograph.

Camera Obscura—Battista della Porta—Leonardo da Vinci

It is popularly supposed that the camera obscura was the invention of an Italian physicist, Giovanni Battista della Porta, of Naples, who lived from about 1540 to 1615, and who describes

the camera obscura in his *Magia Naturalis* (1558) as though it were his own invention. This would make the camera about three hundred years older than photography, but in reality the birth of the camera must have been at least one hundred years earlier, for it is described by Leonardo da Vinci, who lived from 1452 to 1519. It is to be noted that Leonardo does not make any claim to the invention of this camera, which he describes very clearly, so that we may presume the invention existed before his time.

It is supposed by some that the camera was known to our fellow-countryman, Roger Bacon (1214–94), but his remarks might refer equally well to the projection of aerial images:

" The images appear in the air at the junction of the visual rays with the perpendiculars, therefore those looking will run to the image and think the things are there, when there is nothing but merely an apparition ".

This phenomenon was known to Aristotle, who lived from 384 B.C. to 322 B.C., and the principle was made use of in the early part of the nineteenth century in the camera lucida, of which a diagram is shown on p. 6.

Although Leonardo does not claim to be the inventor, his description of the camera obscura is of interest. The following translation of the original MS. is given by Venturi:

" When the images of illuminated objects enter into a very dark chamber by a small round aperture, if you receive these images in the interior of the room on a piece of white paper placed at some distance from the aperture, you will see on the paper all the objects with their proper forms and colours; they will be lessened in size and be reversed and that in virtue of the intersections already noticed. If the images come from a place lit by the sun they will appear as if painted on the paper, which should be very thin and looked at from behind. The aperture should be made in a piece of very thin sheet iron."

It is very interesting to note that Leonardo remarks that the same phenomenon occurs within the eye, and he gives a diagram showing the intersection of the rays at the aperture.

It will be understood that this early camera obscura had no lens, but was in reality a pin-hole camera.

Camera Obscura with Lens

In the first edition of Battista Porta's works, some fifty years later than Leonardo da Vinci, the camera obscura is still without a lens, but in the later edition (1589) of Porta's works the addition of a lens is said to improve the appearance of the image; but there is a still earlier description of a camera with a lens, and the publication of this comes between those of the first and later editions of Porta's works.

Porta's "Magia Naturalis" (1558)

The date of Porta's first edition of *Magia Naturalis* was 1558, and ten years later another author, Daniello Barbaro, published an account of a camera obscura with a lens (1568). Then twenty-one years later comes Porta's later edition of *Magia Naturalis* (1589), in which he not only describes the camera with a lens, but evidently believes this to have been due entirely to his own invention; witness the following quotation from the old English translation of *Magia Naturalis*, or, as the English edition was entitled, *Natural Magick*:

"Now will I declare what I ever concealed till now, and thought to conceal continually. If you put a small lenticular crystal glass to the hole you shall presently see all things clearer, the countenances of men walking, the colours, garments, and all things as if you stood hard by; you shall see them with so much pleasure that those that see it can never enough admire it."

He goes on to say:

"But if you will see all things greater and clearer, over against it set the glass—not that which dissipates by dispersing, but that which congregates by uniting both by coming to it and going from it till you know the true quantity of the image by a due appropinquation of the centre, and so shall the beholder see more fitly birds flying, the cloudy skies, the clear and blue mountains, that are afar off, and in a small circle of paper—what is put over the hole—you shall see as it were an epitome of the whole world, and you shall much rejoice to see it."

Some writers suppose this to refer to the use of concave and convex lenses, but there is little doubt that it was the use of concave and convex mirrors to which Porta referred, the principle of these having been known from the time of Ptolemy and other ancient philosophers.

Barbaro (1568)—Camera with Lens

As Barbaro's description of a camera with a lens is believed to be the first record, it will be of interest to see what he says:

"Having made a hole in the window of the room from which you wish to observe, as large as a spectacle glass, then take an old man's glass convex on both sides, not concave, like the glasses of youths with short sight, and when it is fixed in the hole, shut all the windows and doors of the room so that no other light may enter except by the lens. Now take a sheet of paper and place it in front of the glass so that you see clearly all that is outside of the house. This takes place most distinctly at a determinate distance, found by bringing the paper nearer to or farther from the glass till you have found the proper position. Here you will see the images on the paper as they are, and the gradations, colours, shadows, movements, clouds, the rippling of water, birds flying, and everything that can be seen. For this experiment the sun must be clear and bright because the sunlight has great power in bringing out the visible images. When it pleases you to make the experiment you should choose the glasses which do best and should cover the glass so much that you leave a little of the circumference in the middle which should be clear and open, and you will see a still brighter effect. Seeing, therefore, on the paper the outline of things, you can draw with a pencil all the perspective, and the shading and colouring according to nature, holding the paper tightly till you have finished the drawing."

In the foregoing description by Barbaro (1568) it is interesting to note the stopping down of the lens, and when he speaks of this giving a brighter image, it is evident that he means a more clearly defined image.

It may well be that the application of a spectacle lens to the camera was prior to the time of Barbaro, but as Porta does not mention this in his first edition of *Magia Naturalis* (1558), the introduction of the lens was probably made between 1558 and 1568, the latter being the date of Barbaro's publication. There are statements which appear contradictory, some saying that Porta was the first to describe the camera obscura, and others stating that Leonardo da Vinci's was the first description, but the matter is quite clear, if we note that Leonardo described the camera obscura before 1519 (*the date of his death*), but his description remained in

MS., whereas Porta published a book in 1558, in which he gives a description of the camera. In both these cases there is no lens, but Barbaro published an account of the camera with a lens in 1568.

Pin-hole Inverted Image

Excepting for the introduction of the lens, one might say that there was no invention of the camera, as the inverted image was a natural phenomenon, which must have been observed very generally in the East, where there was much sunshine and many darkened rooms with white walls. It is more rarely observed in this country, though the present writer vividly remembers seeing it once when he was ten years of age.

On this occasion the writer had risen early one bright summer morning to go out of doors to learn to ride one of the old-fashioned bicycles with a 42-inch wheel. On coming downstairs he observed on the large ground glass of the inner door of the house a beautiful image of the fields and trees in front of the house, and it was apparent that the light was coming through the keyhole of the outer wooden door. What surprised the writer was that the image should be upside down, and he did not rest content until he understood the reason of this. Only on one other occasion has the writer seen the same phenomenon produced naturally without intention, but in the East it is quite different. Major-General Waterhouse, I.S.C., who has done much useful work in connection with the early history of the camera obscura, writes:

" In my early days in India, when living in a little bungalow, I constantly saw the natural phenomenon of inverted images of outside objects in the sunshine being vividly depicted on the white walls of the inner, darkened room through the key-hole or a chink in the closed, wooden, folding door leading from the entrance."

It was suggested by Barbaro in 1568 that the image might be traced as it appeared upon the paper screen, and Porta also made mention of this.

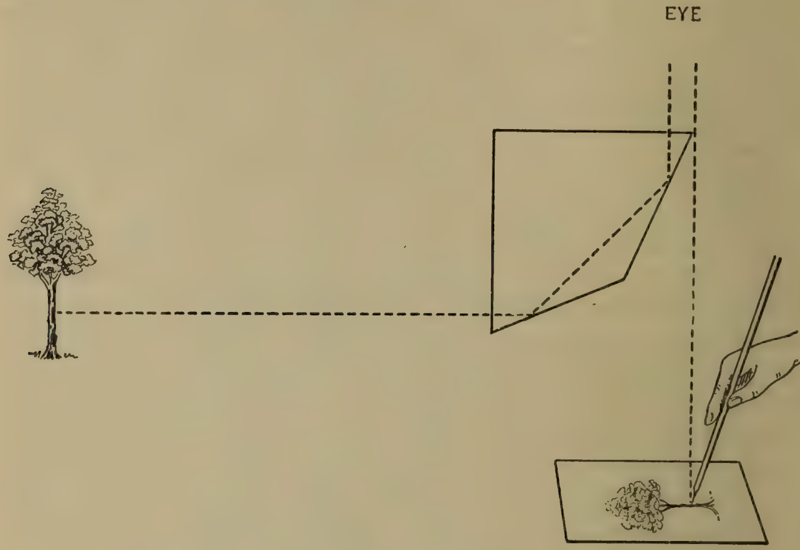
" If you cannot draw a picture of a man or anything else, draw it by this means."

This method of drawing from nature does not seem to have become popular.

Camera Lucida

Another optical instrument was made later, and was known as the *camera lucida*, in contrast to the camera obscura.

In the camera lucida the light entered a quadrilateral prism of glass, as in the following diagram.



It will be observed that the sensation transmitted by the eye to the sensorium is that of an image placed about one foot below the prism, where the paper serves to form a background for the image. This is a *virtual image* seen only by the observer and not visible to all present, as in the case of a camera obscura in which the image is a real one.

Tracing the Image

We have seen that the idea of copying the camera image by pen or pencil is practically as old as the camera obscura itself, as it was suggested by Barbaro and also by Porta, and it is interesting to note that the great astronomer Johann Kepler (who was contemporary with Galileo) used the camera obscura as a means of producing landscapes. The following extract is from the letter of an English traveller to Sir Francis Bacon, and was written during a visit to Kepler when he was fifty years of age (1620):

" . . . A Landskip. Set up a little black tent in a field, made easie, portable and convertible as a windmill to all quarters at pleasure; . . . exactly close and dark save at one hole, an inch and a half diameter to which apply a large prospective trunck, with a convex glasse; fitted to the said hole, and the concave taken out at the other end which extendeth into the middle of this erected tent through which the visible radiations of all the objects without are intermitted, falling upon a paper which is accommodated to receive them, and so trace them with pen in their natural appearance, turning this your little tent round by degrees till you have designed the whole aspect of the place. . . . Surely no painter could exceed the precisenesse of these."

Permanent Image—Early Fancies

The idea of Nature herself being capable of producing permanent images was introduced into a French novel published in the year 1690. This book was entitled *Un Voyage Supposé* and was written by Fénelon. A copy of this is in the possession of the Bibliothèque Nationale, Paris.

One of the earliest ideas was that of great vessels of gold and silver containing water which reflected the surrounding scene, and the water then froze and retained the picture permanently, but much more interesting is an idea contained in a French novel written by Tiphaigne de la Roche in 1760, under the title of *Giphantie*.[1]

He dreamt he was in the very heart of Africa, where he was conducted by his guide into a darkened chamber. He saw out of a window a great scene which seemed to be a quarter of a mile distant. We may imagine his surprise upon seeing an ocean in the heart of Africa. It seemed to him a miracle, as his own words will show:

" I hastily ran to convince my eyes of so improbable a thing. But in trying to put my head out of the window I knocked it against something that felt like a wall. Stunned by the blow and still more with so many mysteries, I drew back a few paces. ' Thy hurry,' said the guide, ' occasions thy mistake. That window, that vast horizon, those black clouds, that raging sea, are all but a picture. The elementary spirits have composed a most subtle matter by the

[1] It will be observed that this title contains exactly the same letters which make his surname.

help of which a picture is made in the twinkle of an eye. They do over with this matter a piece of canvas and hold it before the objects they have a mind to paint. The first effect of the canvas is that of a mirror. But what the glass cannot do, the canvas, by means of the viscous matter, retains the image. The impression of the images is made the first instant they are received on the canvas which is immediately carried away into some dark place. An hour after the subtle matter dries, and you have a picture so much the more valuable that it cannot be imitated by art or destroyed by time.' "

This fanciful dream was written nearly seventy years before the birth of photography, and yet the writer had the idea of the light producing the images " the first instant they are received upon the canvas ", and he had the idea also of then hurrying the picture into some dark place until the image was fixed.

While this seeming prediction of photography is of interest, it took no part in the evolution of photography. It was not till the opening years of the nineteenth century that an actual attempt was made to entrap, by chemical means, the image of the camera obscura.

Silver Nitrate—Thomas Wedgwood (1802)

In 1802 Thomas Wedgwood communicated a paper to the Royal Institution entitled " On an Account of a Method of copying Paintings-upon-glass [1] and of making Profiles, by the Agency of Light upon Nitrate of Silver. Invented by T. Wedgwood, Esq., with observations by H. Davy." In this paper Wedgwood says:

" The images formed by means of a camera obscura have been found too faint to produce, in any moderate time, an ' effect ' upon the nitrate of silver. To copy these images was the first object of Mr. Wedgwood in his researches on the subject,[2] and for this purpose he first used nitrate of silver, which was mentioned to him by a friend [3] as a substance very sensible to the influence of light;

[1] I have made a compound word of paintings-upon-glass, as otherwise some might think that he made his copies upon glass, whereas it meant copying paintings which were on glass and therefore were transparent, so that they could be copied by the agency of light on sensitized surfaces of paper or white leather.

[2] It is evident that it was Davy who composed the paper communicated by Wedgwood and himself to the Royal Institution.

[3] The friend was probably Dr. Lewis's assistant, who had become secretary to Josiah Wedgwood. Lewis's connection with the following up of Schulze's early experiment is related in the text.

but all his numerous experiments as to their primary end proved unsuccessful. In following these processes, I have found that the images of small objects, produced by means of a solar microscope, may be copied without difficulty on prepared paper. This will probably be a useful application of the method; that it may be employed successfully, however, it is necessary that the paper be placed at but a small distance from the lens."

Fox Talbot and Wedgwood—"Pencil of Nature" (1844)

Fox Talbot refers to this paper in the introductory remarks of his *Pencil of Nature* (1844).

"Some time previously to the period of which I have been speaking (1838), I met with an account of some researches on the action of light, by Wedgwood and Sir H. Davy, which, until then, I had never heard of. Their short memoir on this subject was published in 1802 in the first volume[1] of the *Journal of the Royal Institution*. It is curious and interesting and certainly establishes their claim as the inventors of the photographic art, though the actual progress they made in it was small. They succeeded, indeed, in obtaining impressions from solar light of flat objects laid upon a sheet of prepared paper . . . and with respect to the principal branch of the art, viz. the taking of pictures of distant objects with a camera obscura, they attempted to do so, but obtained no result at all, however long the experiment lasted. While therefore due praise should be awarded them for making the attempt, they have no claim to the actual discovery of any process by which such a picture can really be obtained."

Fox Talbot—Niepce—Daguerre

Then followed the work of William Henry Fox Talbot, which commenced before 1835, for in that year he secured a camera photograph (on a paper negative) of his country residence, Lacock Abbey; but before proceeding further, it should be noted that

[1] While this is referred to as the first volume of the *Journal of the Royal Institution*, it should be noted that there was only the one volume. The present writer has asked Sir James Dewar (president of the Royal Institution) the reason for the *Journal* not being continued, and he replied: " . . . that in addition to the first volume there is in the library of the Royal Institution the first eighty pages of a second volume. Whether this volume was ever completed, or if not, why it was discontinued, I regret that at the moment I am unable to say."

between the dates of Wedgwood's and Talbot's experiments, Niepce and Daguerre were at work in France, seeking to obtain the camera image by a different method.

Without seeking in any way to detract from the great work of these French pioneers, the writer desires to point out that their work does not directly enter into the true evolution of photography, further than that the daguerrotypes obtained by Daguerre greatly stimulated interest in the possibilities of the camera.

The work of these two great French pioneers forms a side branch, which, though not in the main track, did certainly take part in the evolution of photo-mechanical printing.

Early Records of Photo-chemical Action

It will be of interest to trace from the earliest records all knowledge of photo-chemical phenomena, even though these may not have taken part directly in the evolution of photography.

If the following legend be true, we might say that photography was possible in the days of Barbaro and Battista Porta. The legend says that at that very time an alchemist, who was seeking in vain for the *philosopher's stone* and the *elixir vitæ*, chanced to drop some ordinary sea-salt into a solution of silver nitrate, whereupon the liquid became white like milk, and that when the sunlight fell upon this liquid it became black immediately. As this phenomenon would not seem to lead the alchemist any nearer his goal, he would not trouble to carry the matter further.

It certainly seems a probable thing that the alchemists who made silver nitrate would become aware of the photo-chemical action of light. It was well known in the sixteenth century that silver ore sometimes changed colour when brought out of the dark mine, but the action might have been put down to exposure to the moist air.

Schulze (1727)—Silver Nitrate

The earliest recorded experimental observation (discarding the legend already mentioned) was made in 1727 by a German physician, Johann Heinrich Schulze. He was not seeking any photo-chemical action; he was desirous of treating some chalk with nitric acid, thinking to make a phosphorescent substance, and had he been careful to use pure nitric acid he would have missed the discovery which he made. He chanced to use some nitric acid in which he

had previously dissolved some silver. When he mixed this impure acid with the chalk, he happened to be standing near a window, and he observed that wherever the direct sunlight fell upon the white mixture it was turned black immediately, while those parts which were sheltered from the sunlight remained unaltered. What seems to have impressed Schulze was the seeming paradox that light produced darkness. He determined to follow up the matter further, but was disappointed to find that a fresh lot of chalk and nitric acid did not show the photo-chemical action at all. Another lot and yet another lot of chalk and nitric acid were tried without any darkening effect, and then Schulze happened to remember that on the first occasion the nitric acid which he used had been used previously for dissolving a little silver. Thereupon he made a much stronger solution of silver in nitric acid, and the darkening effects were greatly enhanced.

Then followed photographic printing in an embryonic state, for Schulze cut out words and sentences in sheets of opaque paper, and, putting these around bottles containing the white mixture of chalk and silver nitrate, he obtained true photographic impressions of the stencils. It goes without saying that as soon as the contents of the bottle were shaken, the impressions would disappear, and some might consider Schulze's experiment as a mere conjuring trick; but we shall see later that the account of Schulze's experiment, published in 1727, proved a real stepping-stone in the evolution of photography. At the same time the fact should be emphasized that Schulze had no idea whatever of making a permanent record.

Dr. William Lewis (1763)

Schulze's experiments were repeated by Dr. William Lewis, of Kingston-on-Thames (1763). He coated ivory and wood with silver nitrate, and found that these darkened in sunshine. He found also, among other things, that compounds of mercury were sensitive to light. We shall see later that these experiments formed an important connecting-link in the chain of evolution.

A few years after the experiments of Lewis some observations were made upon photo-chemical action by a Swedish chemist, Carl Wilhelm Scheele, who proved that when silver chloride was exposed to sunlight there was formed, in the liquid, metallic silver, which produced the darkened effect. The alchemists of those days knew that silver chloride could be dissolved in ammonia, but Scheele

discovered that the darkened product, obtained by exposure to light, could not be dissolved in ammonia. It was unfortunate that the real significance of this fact was not appreciated, for it would have given the pioneer experimenters a means of fixing their photographic impressions.

Scheele (1777)—Silver Chloride

Scheele exposed a prepared silver-chloride surface to the solar spectrum, and discovered that the part exposed to the violet end of the spectrum was darkened more quickly than the parts exposed under the other colours. The parts under the red and yellow cannot have been darkened at all by the rays falling directly upon them, but Scheele seems to have failed to observe this, as also the extension of the chemical effect beyond the visible spectrum. Probably he did not make the experiment in the dark, so that his sensitized surface would not be protected against white light, upon which the direct rays from the prism would be superimposed.

Ritter (1801)—Ultra-violet Rays

These experiments of Scheele were published in 1777, and not till twenty-four years later was it discovered that there was a photochemical effect from rays beyond the visible violet rays of the spectrum. It was Ritter who made this discovery in 1801, and he observed that these ultra-violet rays were more powerful than the visible violet rays.

The Wedgwoods

The next connecting-link in the chain of evolution is of special interest, as it shows how further experiments came to be made in this country. We have seen that Dr. William Lewis (1763) repeated Schulze's experiments and extended them to ivory and wood. It so happened that upon the death of Dr. Lewis (1781) his notebooks relating to these experiments were bought by the famous English potter, Josiah Wedgwood, who also took Dr. Lewis's assistant into his own service as secretary and chemical assistant.

This secretary, whose name was Chisholm, seems to have acted also as tutor to Wedgwood's young son, Tom, who was delicate and who developed a liking for chemical experiments.

Thomas Wedgwood—The Lunar Society

Young Thomas Wedgwood would doubtless receive much inspiration from the scientific friends who gathered at his father's house. Josiah Wedgwood was a member of a small and select scientific society, named *The Lunar Society*, which had no connection with the moon, excepting that its meetings were always held each month on the Monday nearest the full moon, " in order to have the benefit of its light in returning home ". This society was limited to a membership of eight or ten scientists, and it will be of interest to scan the following list of some of its members:

Josiah Wedgwood (potter).
Rev. Joseph Priestley (the father of pneumatic chemistry).
James Watt (of steam-engine fame).
Matthew Boulton (Watt's partner).
Dr. Erasmus Darwin (grandfather of Charles Darwin).
William Murdoch (inventor of coal-gas illumination and manager of Watt & Boulton's works).
William Herschel (the founder of stellar astronomy).

Lewis—a Link between Schulze and Wedgwood

There is no doubt that young Thomas Wedgwood would hear of Schulze's experiments in connection with some of the discussions at the meetings, some of which were held in his own home, for Dr. Priestley was conversant with Schulze's experiments, which he describes in his paper " History of Discoveries relating to Light Vision and Colour ". Then there were Dr. Lewis's notebooks, which were in Wedgwood's house, also the tuition from Lewis's assistant, so that there is a real link between the work of Schulze and that of Thomas Wedgwood, whose paper " An Account of a Method of copying Paintings-upon-glass, and of making Profiles, by the Agency of Light upon Nitrate of Silver " was published in 1802. There is reason to believe that Wedgwood began his experiments in photography when he was nineteen years of age (1790).

One finds his father, Josiah Wedgwood, being credited sometimes with this photographic work, but he died in 1795, which was seven years before the publication of the paper to the Royal Institution.

The Paper by Wedgwood and Davy

The paper of Thomas Wedgwood and Sir Humphry Davy commences with these words:

" White paper, or white leather, moistened with solution of nitrate of silver, undergoes no change when kept in a dark place; but, on being exposed to the daylight, it speedily changes colour, and after passing through different shades of grey and brown, becomes at length nearly black ".

Further, they say that leather is more easily acted upon than paper.

Thomas Wedgwood, who was the fourth son of Josiah Wedgwood, was only thirty-four years of age at his death, having been delicate from infancy. His life was occupied in travelling from place to place in search of health, and there is no doubt his photographic work would have gone much further but for his ill-health. This handicap helps to explain why Wedgwood never succeeded in " fixing " the photographic imprints which he obtained, though one would have thought that, with the co-operation of so great a chemist as Sir Humphry Davy, he would have discovered a fixing agent, more especially as common salt would have served the purpose, and the hyposulphite had been discovered three years before this time. At this time Davy was twenty-three years of age, while Thomas Wedgwood was twenty-nine. In the published paper they say:

" No attempts that have been made to prevent the uncoloured parts of the copy or profile from being acted upon by light have as yet (1802) been successful. They have been covered with a thin coating of fine varnish, but this has not destroyed their susceptibility of becoming coloured, and even after repeated washings, sufficient of the active part of the saline matter will still adhere to the white parts of the leather or paper, to cause them to become dark when exposed to the rays of the sun."

Davy

Some may wonder why Davy did not follow up the experiments further, but during the remaining twenty-seven years of his life, the last few years of which, on account of his health, were spent abroad, where he died at the age of fifty-one, his time was taken up with so many questions of great importance that one can quite

understand this subject of photography having to be laid aside. At the time of the publication of Wedgwood's paper, in which he co-operated, Davy was busy with his famous experiments on the electro-separation of potassium and sodium. The chief point in Wedgwood's work which requires to be emphasized is that he was the first to realize the possibility of getting light itself to make permanent the images of the camera.

Wedgwood and Davy—their Influence on Fox Talbot

Passing over the work of Niepce and Daguerre for the moment, we come to the work of Fox Talbot, which is an extension of the Wedgwood and Davy experiments which were published while Talbot was only two years of age. Talbot says in his *Pencil of Nature*, when speaking of the year 1838:

"Some time previously to the period of which I have now been speaking, I met with an account of some researches on the action of light, by Wedgwood and Sir H. Davy, which, until then, I had never heard of". (Then he refers to the paper of 1802.)

From this remark one might be inclined to delete Wedgwood and Davy's work from the direct line of descent in the genealogic tree, as Talbot's work did not spring from theirs; but in another part of *The Pencil of Nature* Talbot tells us:

"The next interval of sufficient leisure which I found for the prosecution of this inquiry was during a residence at Geneva in the autumn of 1834. The experiments of the previous spring were then repeated and varied in many ways, and having been struck with a remark of Sir Humphry Davy's, which I had casually met with—that the iodide of silver was more sensitive to light than the chloride, I resolved to make trial of the iodide."

He then proceeds to tell of the contradictory results which he obtained, and to which reference will be made later; for the present, we merely note this connection with Davy's work, which was in 1834, and was prior to Talbot's production of his first photograph, which was in 1835, and so we may leave Wedgwood and Davy in the true genealogic tree.

William Henry Fox Talbot (1800-77)

William Henry Fox Talbot was born at Lacock Abbey, near Chippenham, Wiltshire, on 11th February, 1800. He was a grandson of the Earl of Ilchester, of whom his mother was a daughter.

Talbot was educated at Harrow, and then proceeded to Trinity College, Cambridge, where he distinguished himself as a scholar. He devoted some time to politics, being a member of the House of Commons in the first Parliament after the passing of the Reform Bill, but his real interests were in science, and after two years he retired from politics in order to devote his time to scientific investigation.

How the Idea of Photography occurred to him

Talbot commenced his photographic experiments as early as 1833, and he tells us how the idea of photography occurred to him.

At that time (1833) he had not heard of the work of Wedgwood and Davy, nor had he heard of the experiments of Niepce and Daguerre. Talbot happened to use a camera lucida—to which reference has been made already—and with this he tried to sketch the Lake of Como, in Italy, but he found it no easy task. In describing this attempt Talbot writes:

"When the eye was removed from the prism—in which all looked beautiful—I found that the faithless pencil had only left traces on the paper melancholy to behold. I came to the conclusion that the instrument required a previous knowledge of drawing, which unfortunately I did not possess."

As the camera obscura seemed simpler, the image being a real one, and not a virtual one as in the camera lucida, Talbot attempted to sketch its pictures, but he says:

"It baffles the skill and the patience of the amateur to trace all the minute details visible on the paper, so that in fact he carries away with him little beyond a mere souvenir of the scene, which, however, certainly has its value, when looked back to in long after years."

Talbot goes on to tell us how it was the beauty of the pictures in the camera obscura which led him to the idea of photography: ". . . the inimitable beauty of the pictures of Nature's painting, which the glass lens of the camera throws upon the paper in its

focus—fairy pictures, creations of a moment, and destined as rapidly to fade away".

Talbot's Line of Thought

Talbot reflected how very charming it would be if these pictures would but imprint themselves upon the paper on which they fell. The thought was quite original in the mind of Talbot, and it is of interest to follow how he reasoned out the matter. He argued that if you divest the camera image of the ideas which accompany it, and consider only its ultimate nature, it is but a succession or variety of stronger lights thrown upon one part of the paper and of deeper shadows on another. Again, light can exert an action, and in certain circumstances it does exert one, sufficient to cause actual changes in material bodies. If it were only possible to prepare a paper in some manner so that it would be acted upon by light, and visibly changed by light falling upon it, might the variegated scene of light and shade not leave its image or impression behind?

These were the thoughts of Talbot while he was on a visit to Italy, but at that time (1833) he could not conveniently make any experiments. All he could do was to make a careful note of the idea, and of such experiments as occurred to him and seemed likely to help him to realize his ideal, if that were indeed possible. In the quotation made already from *The Pencil of Nature*, it is clear that Talbot was not aware at that time of the experiments which had been made by Wedgwood and Davy thirty-one years previously, but he had read in chemical books that the nitrate of silver was a substance peculiarly sensitive to the action of light, and so it was upon these salts that Talbot built his hopes. The question to be decided by experiment was the time required for this action; he feared it might not be rapid enough for his purpose, and if it turned out to be a very slow action, his whole idea might remain a philosophic dream.

His First Experiments

Having returned home in 1834, Talbot lost no time in trying the experiments which he had noted during the previous year. Taking a sheet of white paper, he carefully brushed it over with a solution of nitrate of silver, and then exposed the prepared paper

to sunlight, but the result was most disappointing; the action of light upon the salts was very much slower than he had hoped. On substituting the chloride of silver, he found it no better. Then the idea occurred to him of trying to form the chloride on the paper instead of merely brushing it on. He made the experiment in the following manner. Having brushed the paper with a solution of sodium chloride (common salt), he let it dry and then brushed it over with a solution of silver nitrate, and thus formed silver chloride on the paper. An exposure of this paper to sunlight gave no better results, but on repeating the experiment, on another occasion, Talbot observed that some parts of the paper darkened much more quickly than others, and on very carefully examining the paper, he thought that these places had been less wetted by the common salt. A further experiment would prove or disprove this idea. He tried a very much weaker solution of the sodium chloride, and then applied the same solution of silver nitrate as he had used in the previous experiment, and the result was most encouraging: the whole surface was blackened rapidly and uniformly. Indeed, he found that too strong a solution of sodium chloride was so destructive of rapid change, that he afterwards used salt to fix his pictures when taken; by washing them in a strong solution of salt, he was able to prevent any further chemical action.

Davy ought to have discovered Fixation

Because of the simplicity of *fixation*, one is surprised that so great a chemist as Sir Humphry Davy failed to discover it, and the surprise is increased when one reads Davy's wording of the paper of 1802, which he wrote along with Thomas Wedgwood. They understood quite clearly that so far as the action of light was concerned, it produced a permanent change, and that the picture was rendered useless by the remaining clear parts darkening in similar fashion when the picture was exposed further to light. Here are their words:

" After the colour has been once fixed upon the leather or paper, it cannot be removed by the application of water, or water and soap, and it is in a high degree permanent ".

Speaking of the photographic pictures which they obtained, they say:

" . . . It may be examined in the shade, but, in this case, the exposure should be only for a few minutes ".

Looking back upon the event now, it seems very strange that Wedgwood, and more particularly Humphry Davy, did not seek to destroy the remaining active salt by chemical means, rather than cover it with a transparent varnish. There is no doubt that it was this difficulty of rendering the pictures permanent that led these experimenters to abandon the subject. Referring to this subject, Fox Talbot says:

" It is remarkable that the failure in this respect appeared so complete, that the subject was soon after abandoned both by themselves and others, and as far as we can find, it was never resumed again. The thing fell into entire oblivion for more than thirty years."

Talbot's Early Attempts (1834)

During 1834 Talbot seems to have contented himself with simply exposing the prepared papers directly to sunlight. He found he could take a photographic impression of any flat objects, such as leaves, lace, &c., by merely laying these objects upon the sensitized paper and then exposing them to light. Attempts were made to secure the picture in the camera obscura, but even when he made an exposure for " a moderate space of time ", by which is meant an hour or so, the results were most disappointing, as may be seen from Talbot's own statement in *The Pencil of Nature*:

" The outline of the roof and chimneys against the sky was marked enough; but the details of the architecture were feeble, and the parts in shade were left either blank or nearly so ".

His First Picture (1835)

Talbot made many experiments to try and hasten the action upon the paper, but he met with no success until the summer of 1835, when he hit upon a real improvement. By giving the paper alternate washings of salt and silver, and then exposing this paper in the camera while the chemicals were still wet, he was able to reduce the time of exposure, from, say, one hour down to ten minutes, provided it was a bright day. The first picture he secured was of his country home, Lacock Abbey, and this he secured in the summer of 1835.

Talbot has several photographs of Lacock Abbey pasted into his *Pencil of Nature*, but these do not include the original photograph, as has been suggested by some; in another place Talbot

tells us that the original photograph was of miniature size, whereas those in his book are whole-plate size.[1]

Talbot's Pictures of Lacock Abbey

Referring to one of the pictures of Lacock Abbey in *The Pencil of Nature*, Talbot says this building

" . . . was the first that was ever yet known to have drawn its own picture. It was in the summer of 1835 that these curious self-representations were first obtained. Their size was very small; indeed they were but miniatures, though very distinct: and the shortest time of making them was nine or ten minutes."

During the next three years no further progress was made, apparently from want of sufficient leisure to experiment, but in 1838 Talbot discovered an entirely new fact.

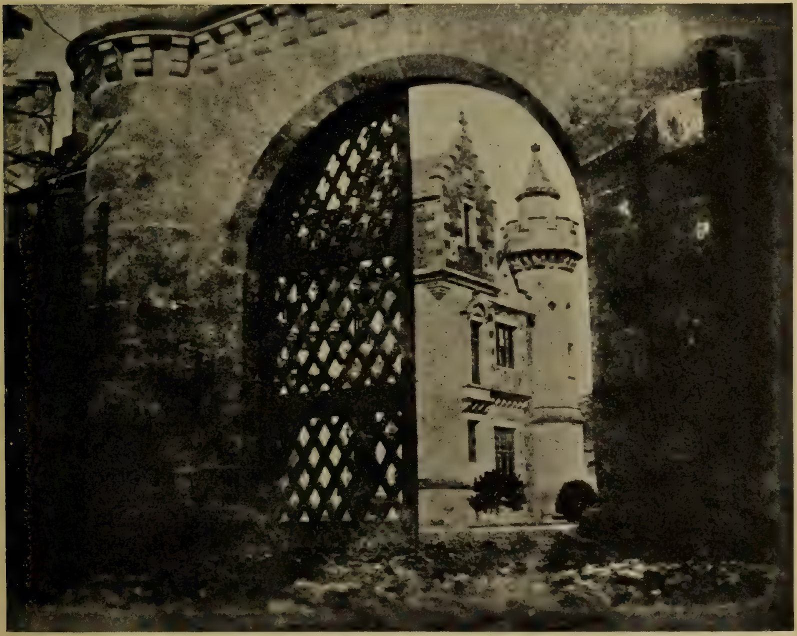
Talbot and Iodide of Silver

In the autumn of 1834, while at Geneva, he had made some experiments with iodide of silver. He tells us that these were suggested by a remark of Sir Humphry Davy, which he had chanced to come across some time previously. The results of his own experiments are related by him in *The Pencil of Nature*:

" I resolved to make trial of the iodide. Great was my surprise on making the experiment to find just the contrary of the fact alleged, and to see that the iodide was not only less sensitive than the chloride, but that it was not sensitive to light at all; indeed that it was actually insensible to the strongest sunshine; retaining its original tint (a pale straw colour) for any length of time unaltered in the sun. This fact showed me how little dependence was to be placed on the statements of chemical writers in regard to this particular subject, and how necessary it was to trust to nothing

[1] The most perfect copy of *The Pencil of Nature* which the present writer has seen is that in the library of the University of Glasgow; in the copy in the British Museum the pictures have faded very much, and some of these have almost entirely disappeared. Talbot published another book a few years later. Its title was *Sun Pictures of Scotland*, and the writer has seen a copy of it in the library of the Patent Office, London. This book is merely a collection of photographs made by Talbot in 1845, and from the fact that one of the photographs has almost disappeared, while the others are in splendid condition (as may be seen by the reproductions in this article), it would seem as though the present difference of condition in the copies of *The Pencil of Nature* may be due to a difference in fixation of the prints, rather than a difference in the chemical effects of the atmosphere, as the present writer had supposed at first.

Melrose Abbey



Abbotsford

From *Sun Pictures of Scotland*, by William Henry Fox Talbot, 1845.

Facing p. 20

but actual experiment; for although there could be no doubt Davy had observed what he described under certain circumstances—yet it was clear also, that what he had observed was some exception to the rule and not the rule itself. In fact, further inquiry showed me that Davy must have observed a sort of subiodide in which the iodide was deficient as compared with the silver: for as in the case of the chloride and subchloride the former is much less sensitive, so between the iodide and the subiodide there is a similar contrast, but it is a much more marked and complete one."

Talbot and Daguerre (1838)

These experiments had been made by Talbot in 1834, and in 1838 it so happened that he had spread a piece of silver leaf on a pane of glass, and thrown a piece of iodine upon it, whereupon he observed coloured rings form themselves on the silver around the particle of iodine. It was evident that these rings must be layers or films of the iodide of silver. Talbot's astonishment was far greater when, on bringing the plate to the window, he found the rings to change colour, and to assume unusual tints. In order to see if these coloured rings would remain permanent, or suffer further changes, Talbot laid the plate aside for a time. It is possible that Talbot's next experiment might have been to test the sensitivity of the iodide of silver on a metal surface; he had no occasion to go further, for at this time Daguerre announced his great discovery on these lines. But even had this not happened, and had Talbot proceeded further, he would have been leaving what has proved to be the true evolution of photography. It was Talbot's negative and positive which carried the day.

Daguerre's Announcement—Publication of Talbot's Results

Immediately following Daguerre's announcement (*in which he gave no particulars of his methods*), Talbot got Michael Faraday to show some of his results to an audience at the Royal Institution, and a month later he sent a paper to the Royal Society describing his methods. Daguerre's methods were not made known until about six months later.

There was no lack of names for different phases of Talbot's work, as is evident from the following, which are all to be found

in a small manual of photography published in 1850. In this book these names occur: *Fluorotype*, *Ferrotype*, *Chromatype*, *Chromotype*, *Chrystotype*, *Cyanotype*, *Catalysotype*, *Authotype*, *Energiatype*, *Hyalotype*. These are all in addition to Talbot's own suggestion of *Calotype* (beautiful pictures), which out of compliment to him was changed to *Talbotype*.

Talbot's Calotype Process (Patented 1841)

In this calotype or talbotype process, the paper was impregnated with silver iodide, and then, before placing it in the camera, it was washed over with a mixed solution of silver nitrate and gallic acid. After exposure in the camera, there was very little visible change, though generally a very faint image might be seen; but when the exposed paper was washed over with more of the gallic acid and silver solution, and gently heated before the fire, the image gradually appeared upon the paper and ultimately became a dense black. This process was patented by Fox Talbot in 1841. In Talbot's second paper to the Royal Society we find:

"PART II. THE CALOTYPE PROCESS.—All the previously related experiments were made in ignorance that there exists a latent image upon the paper after the camera has been in action for a few moments. It must be so, indeed, theoretically, but it was not known that by any means the image could be made to appear. The discovery of the latent image and the mode of its development was made rather suddenly on September 20 and 21 (1840). This immediately changed my whole system of work in photography. The acceleration obtained was so great, amounting to full *one hundred times*, that, whereas formerly it took me an hour to take a pretty large camera view of a building, the same only took now about half a minute. . . . I soon drew up an account of this new process, which I named the Calotype."

The Latent Image

He suggested the name calotype in a letter to the editor of the *Literary Gazette*, in which he gave also a full description of how he discovered the latent image. This point is of so much importance that the following extract may be of interest. In a letter to the editor of the *Literary Gazette*, of date 19th February, 1841, which Fox Talbot sent from Lacock Abbey, he says:

"I may as well begin by relating to you the way in which I discovered the process itself. One day, last September, I had been trying pieces of sensitive paper, prepared in different ways, in the camera obscura, allowing them to remain there only a very short time, with a view of finding out which was the most sensitive. One of these papers was taken out and examined by candlelight. There was little or nothing to be seen upon it, and I left it lying on a table in a dark room. Returning some time after I took up the paper, and was very much surprised to see upon it a distinct picture. I was certain that there was nothing of the kind when I had looked at it before, and, therefore (magic apart), the only conclusion that could be drawn was that the picture had unexpectedly *developed itself* by a spontaneous action. Fortunately I remembered the particular way in which this paper had been prepared, and was therefore enabled immediately to repeat the experiment. The paper, as before, when taken out of the camera, presented hardly anything visible; but this time, instead of leaving it, I continued to observe it by candlelight, and had soon the satisfaction of seeing a picture begin to appear, and all the details of it come out one after another.

"In this experiment, the paper was used in a moist state, but since it is much more convenient to use dry paper if possible, I tried it shortly afterwards in a dry state, and the result was still more extraordinary. The dry paper appeared to be much less sensitive than the moist, for when taken out of the camera after a short time, say a minute or two, the sheet of paper was absolutely blank.

"But nevertheless, I found that the picture existed there, *although invisible*; and by a chemical process analogous to the foregoing, it was made to appear in all its perfection. . . . I know few things in the range of science more surprising than the gradual appearance of the picture on the blank sheet, especially the first time the experiment is witnessed."

It is interesting to note that Queen Victoria and the Prince Consort practised the art of talbotype, having a dark room equipped at Windsor.

Supporting Film—Niepce de Saint-Victor (1848)

In 1848 Niepce de Saint-Victor, who was a nephew[1] of the original Niepce, used a film of albumen on a sheet of glass

[1] This Niepce, who is usually called Niepce, Junior, is sometimes stated to have been a son of Joseph Nicephore Niepce, who made the original experiments

to hold the sensitive compound. He coated the glass with white of egg and potassium iodide, and when this was dry he treated it with a solution of silver nitrate, and this was exposed either in the wet or dry state in the camera, and afterwards developed with gallic acid.

It should be noted that in this method Niepce de Saint-Victor was the first to use a film on the glass for carrying the sensitive salts. Glass plates had been used some time previously (1840) by Sir John Herschel, but he had no supporting film, merely placing the silver salt solution on the glass.

The Petzval Lens (1840)

In 1840 Professor Joseph Petzval introduced his portrait lens. He was professor of mathematics in the University of Vienna, and, finding that it was necessary to have more light in the camera, he set about to design a lens of larger aperture, and calculated the necessary composition of such a compound lens. It is remarkable that this Petzval lens holds its own to-day, after eighty years of active progress.

Collodion (1848)

The next step of great importance was the introduction of collodion. Although a method of nitrate cellulose had been discovered in 1846 by Schoenbein, and although its application to photography seems to have been suggested first by Le Grey of Paris, it was F. Scott Archer (England) who first used it in the making of photographic negatives. This he had done in 1848, although he did not publish an account of his process until 1851; this was published in *The Chemist*.

The collodion formed a coat upon the glass and contained a soluble iodide or an iodide and a bromide. This produced a jelly-like film when the solvents had evaporated, and the plate was then immersed in a solution of silver nitrate, whereupon invisible silver halide is formed, and this remains embedded in the film. The

with bitumen, but he was only a nephew. The confusion doubtless arises from there having been a son, Joseph Isidore Niepce, who was accepted by Daguerre as a partner on the death of the original partner. In this connection the writer desires to point out that it is to Daguerre's credit that he included this son in the claim for the invention, which he put before the French Government, for, long before that time, Daguerre had abandoned entirely the bitumen process of Niepce.

collodion plate was exposed in a wet condition, and was developed with an acidified solution of pyrogallol, which developer was replaced later by an acidified solution of ferrous sulphate.

Dry Plates

Then followed the dry collodion plate, and about sixteen years later Dr. R. L. Maddox published a formula for preparing a dry gelatine emulsion of silver bromide. It was a very imperfect process, but it led up to the gelatine-bromide process of to-day. It was in 1878 that Charles Bennett, whose family are well known as hatters, exhibited some photographs which he had taken with remarkably short exposures. He obtained this success by a process of heating after the film was formed, keeping the plate about 90° F. for several days or even for a week. It was soon discovered that a few minutes at the temperature of boiling water was as effective as Bennett's slower process of heating in obtaining a very sensitive plate.

A year later Mr. Joseph Paget offered a prize of fifty pounds for the best dry-plate process, and the Paget Prize Plate Company followed, and by 1880 there were several makers of dry plates.

Joseph Nicephore Niepce (1765–1833)— His Independent Work

The scope of this introduction does not take us any further, but it will be of interest to consider the part played by Niepce, whose only practical memorial to-day lies in the field of photomechanical printing, and by Daguerre, whose beautiful pictures did so much to popularize the art of the camera.

In the genealogic tree the writer has placed Niepce's work as disconnected with the discoveries of Schulze and of Wedgwood and Davy. Niepce's work was in no way dependent upon what had gone before; he began on entirely different lines.

In 1813 Joseph Nicephore Niepce was a middle-aged country gentleman, having been born near Chalon-sur-Saône, in South-Eastern France, in the year 1765. He had been educated for the Church, but at the time of the French Revolution he became a soldier. When peace came, he settled down to scientific investigations.

Niepce's Early Results

Niepce wondered if it would be possible to save the draughtsman the labour of copying designs upon lithographic stones, which work was new at that time, and had just been introduced into France. His idea was to find some substance which would be sensitive to light, and which could be exposed beneath a drawing made on a transparent background. He substituted a metal plate for the lithographic stone, and this plate he coated with various varnishes.

After three years' experimenting he succeeded (1816) in obtaining photographic prints of line drawings, though these could not be used for the purposes of lithography.

In 1818 he made an attempt to arrest the picture of the camera obscura, and he met with some measure of success, but his correspondence does not make it clear at what date he succeeded.

Heliographs

In 1826 Niepce found that the mineral pitch known as *bitumen of Judea* was the best substance for his purpose. He found that it was soluble in oil of lavender, but that where exposed to light it was rendered insoluble. He placed a thin coating of the bitumen upon a metal plate, exposed it to light beneath a line drawing, and then washed the plate in oil of lavender, so that those parts which had been protected by the lines of the drawings were dissolved and the metal plate was thus exposed at these places, producing what the inventor called a " heliograph " or sun-drawing.

Origin of Photo-mechanical Printing

Niepce sought to make his sun pictures more visible, but, as the original idea was to print copies as in lithographs, he endeavoured to make these heliograph plates into printing plates. This he succeeded in doing by placing the heliograph in a bath of acid, so that the bare parts of the plate, which represented the lines of the drawing, were eaten into by the acid, and so we see the birth of present-day photo-mechanical printing processes, which took place eighty years ago in the laboratory of Niepce.

In connection with Niepce's success in obtaining pictures in the camera obscura, it is interesting to note the statement in the

Bill presented to the French Parliament in 1839 by the Minister of the Interior:

"M. Niepce, Senior, discovered a method of rendering these images (camera obscura), but though he resolved this difficult problem, his invention nevertheless remained very imperfect. He obtained only a silhouette, or black profile of objects, and twelve hours at least were required to produce even the smallest design."

In his first attempt Niepce used a camera made out of a cigar-box, and with a lens taken from an old solar microscope which had belonged to his grandfather.

Meeting of Niepce and Daguerre (1826)

Niepce dealt with an optician in Paris, named Charles Chevalier, and it so happened that Louis Jacques Mandé Daguerre, when seeking to entrap the image of the camera obscura, went also to the same optician, which fact led to the introduction of Daguerre to Niepce.

At this time Daguerre was not yet forty years of age, while Niepce was sixty, and the two men were very different. Niepce was a country gentleman of independent means; Daguerre was a celebrated theatrical scene-painter. He used a camera obscura to help him in his painting, and in 1824 he became possessed of the idea to get light itself to fix the camera image. His first idea seems to have been to use phosphorescent substances, and produce self-luminous pictures, but when Chevalier, the optician, found how earnest Daguerre was in the same pursuit as Niepce, he told him of Niepce.

Daguerre lost no time in writing to Niepce upon the subject, but received no reply to this letter; Niepce put the letter in the fire, believing it to be merely a ruse on the part of someone anxious to obtain his secret. A year later Daguerre tried again to get into touch with Niepce, stating that he had arrived at important though imperfect results. Daguerre suggested that it might be advantageous to both if they were to make a mutual exchange of their secrets. Niepce made inquiries concerning Daguerre, and, being satisfied that his claims were genuine, he began a correspondence with the scene-painter. Later, they exchanged samples of their work, and ultimately they met and signed a co-partnery agreement.

The Mysterious Young Man with the View of Paris

Chevalier tells a story which it may be of interest to relate at this point. One day about this time a very shabbily dressed young man entered his shop and inquired the price of a convergent meniscus glass lens. The mention of the price made the young man turn pale, whereupon Chevalier asked him what object he had in view. The youth replied that he had succeeded in fixing the image of the camera on paper, but that he had only a very rough apparatus, and yet with this he had succeeded in obtaining views from his window. Chevalier thought " another poor fool who wants to fix the image of the camera obscura ", and he told the young man that he knew several men of science who were engaged with this question, but without the success which he had evidently obtained. As proof of his statement the youth pulled from his pocket a very shabby pocket-book and laid upon the counter a view of Paris as sharp as the image of the camera. Chevalier questioned him as to how he had succeeded, when the youth produced from his pocket a bottle containing a blackish fluid with which he said he had obtained the picture. He promised to return again, but did not appear, and we know not what his fate may have been. Chevalier failed to get any results from the liquid, as also did Daguerre, to whom Chevalier gave the bottle. However, it may be that Chevalier had already left the liquid exposed to light before the attempt was made.

The foregoing story is told by Tissandier in his *History and Handbook of Photography*, and he refers in a footnote to a work of Chevalier entitled *Guide du Photographie*, Paris, 1854, but the present writer has failed to find any reference to the story in that particular work. However, there was another work by the same author, of which the writer has not been able to find a copy.

In relating the story Tissandier says:

" He (Chevalier) well knew that the problem engaged the minds of such men as Talbot and Daguerre, but none the less deemed it a Utopian dream ".

But as the date given by Tissandier is 1825, it is evident that he is in error so far as Talbot was concerned, as he did not commence any experiments, nor had any thought of the subject, until 1833.

Daguerre and Iodine

Up to the time of Niepce's death (1833), neither he nor Daguerre had made much further progress.

Niepce had used iodine to blacken his heliographs, so that Daguerre would have this element amongst his stock of chemicals. It had been discovered in 1811.

It has been said that Daguerre observed one day that a silver spoon lying upon a plate treated with iodine produced an image of the spoon upon the plate. The tale is a probable one, but Daguerre does not mention it in his own writings. In any case, we find Daguerre exposing the polished silver surface of his plates to the fumes of iodine, and thus obtaining a sensitized surface of silver iodide.

The Latent Image—Daguerre's Accidental Discovery

At first there was little hope of this method leading to success, as only a very faint image could be obtained of bright objects, and that after many hours' exposure. However, on one occasion when Daguerre had set up his camera, and had just commenced one of these long exposures, the sun became clouded and he stopped the experiment, placing the prepared plate in a cupboard, so that it might be re-polished and prepared again for another trial when the sun was shining. On removing the spoilt plate from the cupboard the following morning, Daguerre was utterly surprised to find on his plate a beautiful picture of the scene which he had proposed to take the previous day. His joy knew no bounds. He declared that he had arrested the flight of light, and that in future the sun himself would draw his pictures. It remained to repeat this experiment, so, putting a freshly prepared plate in the camera, Daguerre gave a very short exposure, this time intentionally, and, placing the plate in the same cupboard as before, he gave it the same time there as previously, and, taking it out the following morning, he found another beautiful picture. Upon investigation, Daguerre found that it was the fumes of mercury which were affecting the plate while in the cupboard. Here was the discovery of the *latent image*.[1] No image was visible upon the plate until it was exposed to the fumes of mercury. The mercury vapour attached itself to the exposed portions of the silver iodide, forming an amalgam. The plate was then dipped into a solution of sodium

[1] There seems to be no record of the date on which Daguerre discovered the latent image. The present writer has endeavoured to find the actual date of the

thiosulphate, with which the silver iodide formed a soluble compound salt, afterwards removed by gentle washing in the water.

The *short exposure* was only short by way of comparison with previous attempts, and varied from three to thirty minutes.

The daguerreotype plates were made more sensitive by the application of bromine, which was added by Goddard in 1840, and this was enhanced further by Claudet's introduction of chlorine along with iodine.

Reception of Daguerre's Invention

Daguerre's invention caused a great sensation. Many people believed that the profession of the painter had gone for ever. Even the great historical painter, Paul Delaroche, on seeing Daguerre's pictures, declared: "Painting is dead from to-day".

We are not concerned with Daguerre's failure to float a company, nor with the success with which the individual photographers met from 1841 to 1854 (*daguerreotype may be said to have died in the same year as its inventor*, 1851); but what concerns our present purpose is the true historical setting of the various inventors, and the present writer maintains that these inventors got on to a side branch and did not take part in the evolution of modern photography, excepting in so far as Daguerre's beautiful pictures increased the interest of the public in the art of photography and in the discovery of the latent image, which, however, was discovered independently by Talbot in his process some years later.

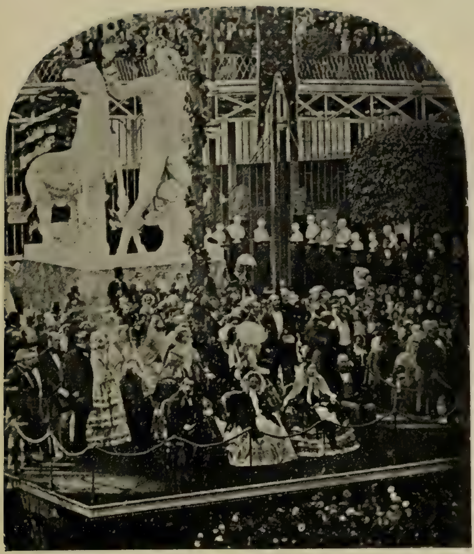
We owe the discovery of the latent image to Daguerre. His method of dealing with the metal plates was of no use to Talbot in his treatment of paper negatives, but the idea of a latent image was entirely due to Daguerre, and some years elapsed before Talbot

discovery, and in this research he has had valuable assistance from Mr. Macfarlan and Mr. Arthur, of the Patent Office library, London, but unfortunately nothing definite can be found. However, there is a letter from Isidore Niepce, written to Daguerre on the 1st November, 1837, which certainly refers to the subject of the latent image.

It will be remembered that Isidore Niepce had succeeded his father in the partnership with Daguerre, and in this letter (1837) he says:

"While I require almost a whole day to make one design, you—you ask only four minutes".

It is evident that Daguerre would have needed more than four minutes of exposure unless he had at that time discovered the latent image, and the assumption is that the letter from Niepce, Junior, was in acknowledgment to Daguerre's announcing to him the discovery of the latent image. This is not definite, but seems a fair assumption to make.



Examples of Daguerreotypes

The upper example shows the opening of the 1851 Exhibition.

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discovered the latent image on a paper negative as described in the quotation already given.

Daguerre and Fox Talbot—Comparison of their Work

It is clear, therefore, that although Daguerre has not been included in the direct genealogic tree of present-day photography, his great work had an indirect influence in the progress of the art.

Fox Talbot followed up the early experiments of Schulze and others, whereas Daguerre abandoned the silver salts, and by means of his polished silver plates he produced excellent photographs; but these had the disadvantage of having to be looked at in a particular way, or they would not be seen at all, and again only one copy was available from each exposure in the camera, whereas Talbot's were clear black-and-white pictures on paper, and any number of copies might be produced from a single negative. Talbot remarks on this himself:

" The number of copies which can be taken from a single original photographic picture appears to be almost unlimited provided that every portion of iodine has been removed from the picture before the copies are made ".

The words *positive* and *negative* were used by Talbot in his writings (1844), but these words were introduced into the nomenclature of photography by Sir John Herschel in 1841.

In these days, when everyone now understands the general principles of photography, it seems strange that Talbot had to make explanations such as the following:

" Groups of figures take no longer to obtain than single figures would require, since the camera depicts them all at once, however numerous they be. . . . If we proceed to the City, and attempt to take a picture of the moving multitude, we fail, for in a small fraction of a second they change their positions so much as to destroy the distinctness of the representation.

" It is so natural to associate the idea of labour with great complexity and elaborate detail of execution that one is more struck at seeing the thousand florets of an Agrostic depicted with all its capillary branchlets (*and so accurately that none of all this multitude shall want its little bivalve calyx, requiring to be examined through a lens*) than one is by the picture of the large and simple leaf of an

oak or a chestnut. But in truth the difficulty is in both cases the same. The one of these takes no more time to execute than the other, for the object which would take the most skilful artist days or weeks to trace or to copy is effected by the boundless powers of natural chemistry in the space of a few seconds."

Talbot and Daguerre—Some Important Dates

Talbot's and Daguerre's methods were entirely independent of one another, but they happened to be making their experiments at the one time, and both obtained a similar amount of success in the one year (1838), both having kept their processes secret.

Daguerre tells us himself that having heard that an Englishman was successfully entrapping the image of the camera, and fearing that the process might be the same as his own, he hastened to announce his results (but not his methods). The order of events is as follows:

1st to 14th January, 1839.—Daguerre announced the results of his process, and kept his methods secret.

25th January, 1839.—Michael Faraday showed exhibits of Fox Talbot's sun pictures to the Royal Institution.

31st January, 1839.—Fox Talbot sent a paper entitled "Some Account of the Art of Photogenic Drawing, or the process by which natural objects may be made to delineate themselves without the aid of the artist's pencil" to the Royal Society, and in this he set forth some particulars of his methods.

21st February, 1839.—Talbot sent a second and fuller account of his methods to the Royal Society. This was entitled "An Account of the Processes employed in Photogenic Drawing".

15th June, 1839.—Daguerre first made known his methods in the Bill put before the French Chamber of Deputies.

Daguerre is deserving of highest praise because of his remarkable perseverance during fifteen years of uphill work, and, as evidence of his intense devotion to this work, it is of interest to note the following incident.

In 1825, at the close of one of the public lectures of the distinguished French chemist Jean Baptiste Dumas, he was consulted by a lady who explained that she was the wife of Daguerre, the painter, and she feared her husband had gone mad. She explained that for some time he had let the idea possess his mind that he

could fix the images of the camera, and she was anxious to know if this were a thing that ever could be done, or had her husband lost his senses. The professor explained that in the present state of knowledge they were unable to do it, but he would not set down as mad the man who tried to do it.

In summing up, it may be said that Daguerre's accidental discovery of the latent image was of the very greatest importance, although its method of development was not applicable to Talbot's process. Talbot discovered the latent image quite independently, as is shown by the quotation on p. 23, from his letter to the editor of the *Literary Gazette*.

Leaving out all details, it may be said that the evolution of photography, as it is practised to-day, is due mainly to Wedgwood and Fox Talbot.

The Evolution of Photography

1727.—Johann Heinrich Schulze discovered accidentally that a pasty mixture of chalk and a solution of silver nitrate darkened when exposed to sunlight. He produced dark images of stencils.

1763.—Dr. William Lewis repeated Schulze's experiments, and left full details in some notebooks.

1777. — Carl Wilhelm Scheele (Sweden) exposed paper (treated with silver chloride) to the solar spectrum, and found the violet end was darkened in 15 seconds, while the green required 37 seconds.

1790.—Thomas Wedgwood obtained some results in photo-copies on paper treated with silver nitrate. His father (Josiah Wedgwood) had purchased the notebooks of Dr. William Lewis.

1802.—Wedgwood and Humphry Davy sent a paper to the Royal Institution giving details of photo-printing with silver nitrate and silver chloride.

1814. — Joseph Nicephore de Niepce (France) made heliographs with bitumen on metal plates.

1824. — Louis Jacques Mandé Daguerre began his experiments in fixing the images of the camera.

1835.—William Henry Fox Talbot took a photograph of Lacock Abbey by means of a paper prepared with silver salts and placed in a camera.

1839. — Talbot's "photogenic drawing" made public.

1839 (January).—Daguerre's discovery of the latent image. His announcement of results but not of methods.

1839 (August).—Daguerre's process made public in a Bill to the French Parliament.

1840.—J. Goddard introduced bromine, in addition to iodine, in sensitizing daguerreotypes (shorter exposures).

1841.—Talbot's "calotype" process with latent image patented.

1848.—Niepce de Saint-Victor introduced a film on glass for carrying the sensitive salts.

1854.—Daguerreotypy ceased.

Photography as practised to-day.

CHAPTER II

The Elementary Optics of Photography

The subject of the optics of the camera is dealt with in Chapter III by Professor Conrady. Here we shall merely give a short account of the more important optical phenomena.

Laws of Geometrical Optics.—It is desirable to recapitulate certain fundamental laws of light-propagation.

The laws of geometrical optics are:

1. *Rectilinear Propagation.*—In a uniform medium light proceeds in straight lines; any *pencil* of light is bounded by straight lines,

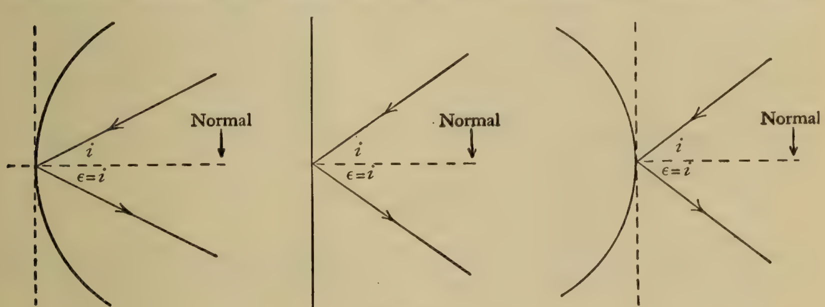


Fig. 1

termed *rays*, and may be considered as composed of a bundle of geometrically related but physically independent rays.

2. *Regular Reflection.*—A ray incident on a smooth surface is partly transmitted, partly reflected; the incident and reflected rays make equal angles with the normal to the surface (see diagrams, fig. 1).

The intensity of the reflected ray increases rapidly with the angle of reflection, ϵ, up to the "critical" angle, when total reflection occurs, no light being refracted. Photographically, this gives rise to (simple) *halation*, seen in the formation of a bright ring or halo around the image of a lumi-

nous object-field, due to total reflection from the transparent support of the film. It is very slight with celluloid film, and may be obviated with glass plates either by use of a non-reflecting, absorbing backing, or by a layer of soluble yellow dye between the emulsion and the glass, which cuts out the active light.

3. *Refraction.*—The ray transmitted when light passes from one medium to another is refracted, i.e. its direction is altered relative to that in the first medium. An *optically-denser* medium is one in which the refracted ray is deviated toward the normal to the surface of separation; conversely an optically-rarer medium is one in which the ray is deviated away from the normal. The ratio of the sines of the angles of incidence and emergence is a constant for the same two media and for light of the same quality. Thus in the figure (fig. 1*a*) if suffix 1 refers to the medium on one side of the plane FG, and suffix 2 to that on the other; n is the refractive index, and θ the inclination of the ray to the normal ED, then

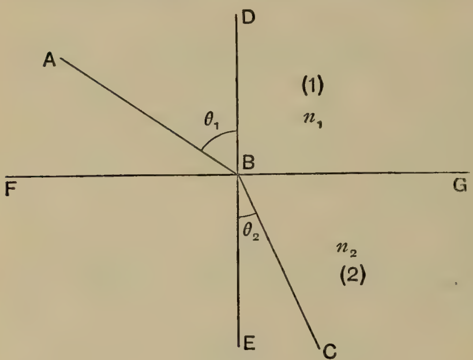


Fig. 1*a*

$$n_1 \sin\theta_1 = n_2 \sin\theta_2;$$

$$\text{i.e. } \frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = \text{a constant for the pair of media.}$$

This constant is called the *relative refractive index.* If the medium denoted by suffix 1 is a vacuum, n_1 is arbitrarily taken as unity, then

$$\frac{\sin\theta_1}{\sin\theta_2} = n_2, \text{ the } \textit{absolute refractive index} \text{ of the medium 2.}$$

For all transparent materials the absolute refractive index is greater than unity.

4. *Coplanar Condition.*—The incident, reflected, and refracted rays lie in the same plane.

It may be noted that all the foregoing laws may be obtained as corollaries of Fermat's *Principle of Least Time.* Suppose a ray of light passes

from a given point A to another B by a series of reflections and refractions, Fermat's principle asserts that the time taken by such a ray of light to pass from the one given point to the other is least when the path pursued is that which is actually followed in nature. The times taken for a ray of light to pass, by different arbitrary paths, from one given point to another can be readily calculated, and it is found that the path determined in accordance with the laws of optics stated above gives the least time of passage. By Fermat's principle it is therefore the natural path.

5. *Complex Nature of White Light. Dispersion of Light.*—The extension of a beam of light refracted by a prism into a multicoloured spectrum (a fact discovered by Newton) shows that white light is

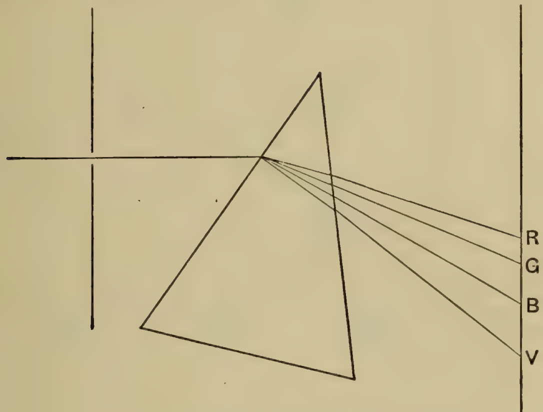


Fig. 2.—Dispersion of White Light by a Prism

composed of rays of different qualities, rays of different colour differing in refractivity. (See fig. 2.)

Physical Optics.—Co-ordinating these laws of geometrical optics, and accounting in addition for the deviations from them, which are found to arise in practical optics, we have the basic theory of physical optics, *the undulatory or wave-theory of light.* According to this theory light is a form of radiant energy, propagated by transverse oscillations of a medium, the ether of space. Whereas the earlier forms of the theory conceived the oscillations as similar to waves in an elastic solid, the electromagnetic theory of Clerk Maxwell regards them as periodic changes of electric charge and magnetic induction, the direction of the oscillating electric force being perpendicular to the magnetic, and both being perpendicular to the direction of propagation of the wave-front. Vibrations of all

periods (or wave-lengths) travel with the same speed *in vacuo*, about 300,000 Km. per second. Calling this velocity c, and the *wave-length* λ, we get $\lambda = ct$, where *t is the periodic time.* The most important evidence in favour of the wave theory is given by *the phenomena of interference.* Any point of disturbance in the ether becomes the centre of a spherical wave spreading out from it. The effect at any point due to two or more waves is the resultant of the superposition of the individual effect of each wave; if the peaks coincide the waves reinforce each other; if the peak of one coincide with the trough of another they may cancel. Interference occurs at the edge of any obstruction to propagation, and gives rise then to diffraction. (See also p. 206, "Interference Photochromy".)

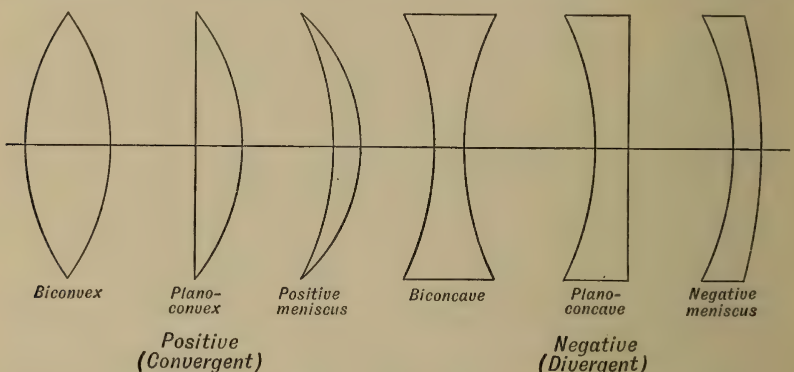


Fig. 3.—Types of Lenses

In the elementary theory of image-formation, diffraction may be ignored, but it plays a fundamental part in the image-formation of minute structures.

Images, Real and Virtual.—If the rays diverging from a point are transformed by suitable means into a convergent pencil, the point of convergence forms the image of the first or *object-point.* If actual convergence takes place, i.e. if the point of convergence lies in the direction of propagation, relative to the object-point, the image is *real*, whereas if only the prolongation of the rays backward in the opposite direction gives the convergence, the image is *virtual. For photography, real images are essential.*

Apertures and Lenses.—Although a very small aperture or pin-hole can be used to form an image, this image is so faintly illuminated that it is practically useless. *The inefficiency of very small apertures is overcome by the use of lenses*; on the other hand, certain

optical deficiencies of lenses are modified by the control of apertures with diaphragms.

A lens may be defined as a transparent medium bounded by curved surfaces—one may be plane—having a common normal. Practically only glass lenses with spherically curved surfaces are used. The two classes of single simple lenses are illustrated in the diagram (fig. 3).

(*a*) *Positive or convergent lenses* bring a parallel beam to a point of convergence or focus; a real image is formed.

(*b*) *Negative or divergent lenses* spread out a parallel beam so that it appears to diverge from a point (virtual focus) on the "object" side of the lens.

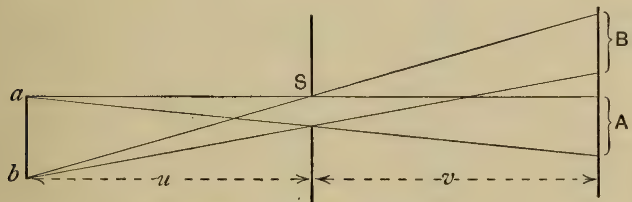


Fig. 4.—A Pin-hole Image

The common normal to the bounding surfaces of a lens is termed *the axis*; in compound lenses all the normals must lie on the axis. Practically all photographic lenses are compound, and correct centring is essential.

Image Formation.—The formation of the image by a small aperture or pin-hole is shown in fig. 4. Each point, as *a* or *b*, of the object is reproduced in the image-plane as a disc-image of the aperture in the screen S. The smaller this aperture, down to a certain limit, the better the definition; beyond this limit diffraction effects become appreciable and prevent any further improvements in definition (Chapter III, p. 55). The image is clearly inverted, and the *scale* or *magnification* of the image, i.e. the ratio AB/*ab*, is evidently equal to $\frac{v}{u}$. Every object-plane has a corresponding image-plane, and this geometrical correspondence is termed the *collinearity of object and image spaces.*

Passing to a simple positive lens (fig. 5), we have an inverted image also, but one of greater intensity of illumination, since all rays collected by the lens may be used.[1]

[1] Subject, of course, to the use of the diaphragm to restrict the aperture of the lens. See p. 45.

Parallel rays (for instance, those coming from an infinitely distant object) are, as already stated, brought to a point, the *principal focus* F (or F′). The distance f (or f') of this point from a certain point N (or N′) on the axis, and characteristic of the lens, is termed *the focal length.* For an infinitely thin lens, this point would be the intersection of the lens and the axis, but for real or thick lenses having two surfaces, there are two points N and N′, termed *the nodal or Gauss points*, such that any ray entering the lens through one (say N) will seem to emerge from the other in a direction parallel to the original direction of the ray (fig. 6).

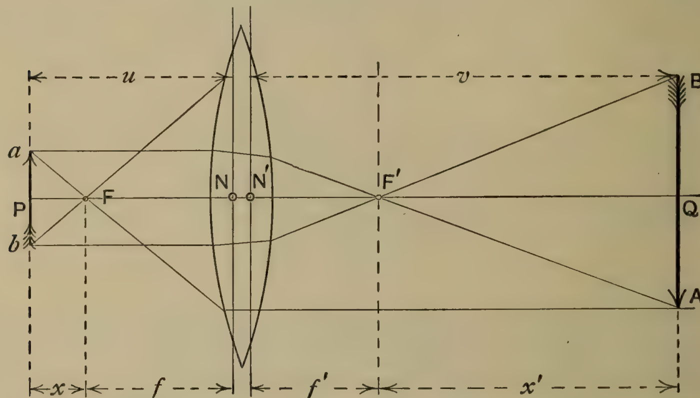


Fig. 5.—Formation of Image by Lens

The plane perpendicular to the axis through N is *the nodal plane of entrance*, and that through N′ is the *nodal plane of emergence* (reciprocally, according to the direction of propagation). In simple single lenses the nodal interspace may frequently be neglected, being small, but account must be taken of it in compound lenses.

In certain lenses one of the nodes coincides with *the rotary centre*, i.e. a point on the axis about any line through which the lens may be rotated without displacement of the image. This is used in panoramic cameras.

Focal Length, Focal Power, and Scale of Image.—The distance from the node of *entrance* to the principal focus is *the focal length of the lens.* The amount of convergence induced on parallel rays increases as the focal length diminishes, and in fact the *focal powers* (which are approximately the measures of curvature of emergent wave-fronts) are inversely proportional to the focal lengths. The *power* of a lens (in diopters) is measured by the recip-

rocal of the focal length expressed in metres. The lens of unit-power (1 diopter) is therefore one whose focal length is 1 metre. The *scale* or *magnification* of the image, i.e. the ratio of its size to that of the object, is equal to the ratio of the distances of image and object from the lens, or, more accurately, from the nodal points respectively. For a given object-distance, the image-distance, and, therefore, the scale, is determined by the focal length. If u (see fig. 5)

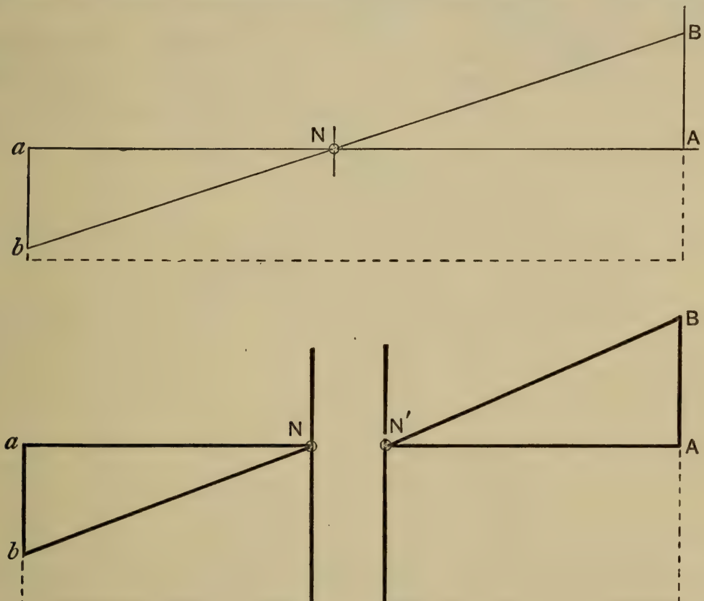


Fig 6.—Nodal Points

be the object-distance from the lens, v the conjugate (image) distance, and F the focal length of the lens, then $\frac{1}{u} + \frac{1}{v} = \frac{1}{F}$. If a real image is being produced by a positive lens, object and image lie outside the principal foci (see fig. 5); then we may measure distances from P and Q to the principal foci. Calling these x and x', the extra-focal distances, we have the simplified formula $xx' = F^2$. The scale of the image, M, is given then by

$$M = \frac{v}{u} = \frac{v - F}{F} = \frac{x'}{F} = \frac{F}{x}.$$

It may be noted that the two principal foci and the two nodal

points are termed *the cardinal points of a lens*; there are other characteristic points of minor importance, which cannot be noticed in this survey.

Focal Length of a Combination of Two Lenses.—The focal length of a combination of two lenses is given by the expression $f = \frac{f_1 f_2}{f_1 + f_2 - d}$, where f_1 and f_2 are the focal lengths of the components, d the optical (internodal) separation.[1]

Orthoscopy and Deficiencies of Lenses.—Exact geometrical correspondence between image and object is termed *orthoscopy*. The image formed by a single simple lens is deficient in

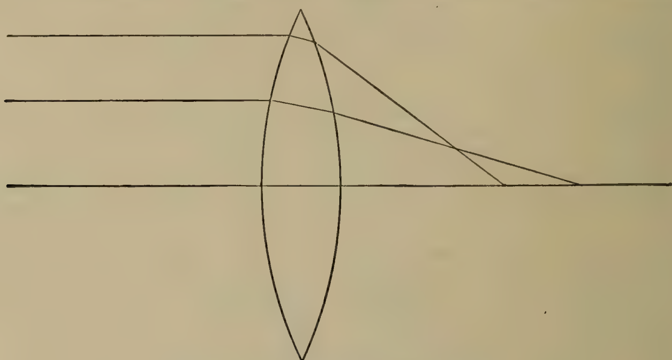


Fig. 7.—Illustrating Spherical Aberration

several respects. The correspondence desired may be analysed into: (*a*) precise definition, i.e. perfect formation of image-points; (*b*) flatness of field, i.e. coplanarity of all image-points; (*c*) congruence, i.e. correct relative position of image-points. Lens deficiencies in these respects are termed aberrations; the most important are:

(1) spherical aberration and coma;
(2) chromatic aberration;
(3) astigmatism;
(4) curvature of field;
(5) distortion.

Spherical Aberration is illustrated in fig. 7. Considering only parallel rays, marginal and central rays cross the axis at different points, so that a sharp focus is not secured. This causes blurred

[1] Measured between the nodal plane of emergence of the front lens and that of the entrance to the rear lens.

definition. Stopping down to a small central aperture improves this, but reduces the illumination of the image by preventing all the light which falls in the lens from reaching the image. Correction is brought about as far as possible by correct choice of lens-form.

Since the aberration is in opposite senses for positive and negative simple lenses, a combination of positive and negative surfaces will reduce the effect to a minimum. It is least for the meniscus type of simple lens. Spherical aberration of oblique pencils is termed *coma*; the image of a point formed by oblique rays is blurred to a pear-shaped figure.

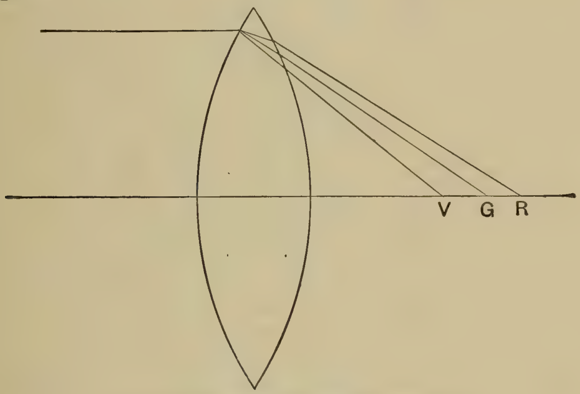


Fig. 8.—Illustrating Chromatic Aberration

Chromatic Aberration is illustrated in fig. 8; it arises from the different refractivity of rays of different colour, i.e. of different wave-length. The difference in the extreme refractive indices divided by the mean refractive index is called the *dispersion*. Flint glass has a greater dispersion than crown glass. Correction is therefore effected by combining a negative lens of flint glass with a positive lens of crown glass, the combination remaining positive. When thus accurately corrected for two colours, e.g. yellow and violet (say 589μ and 434μ), the correction is imperfect for others, and leaves a slight fringe of colour, *the secondary spectrum*. If a third colour is to be accurately corrected, a third lens is required, all three being cemented together. Lenses corrected for two colours are termed *achromats*, for three, *apochromats*.

Astigmatism is a defect shown as unequal definition of groups of coplanar lines lying in perpendicular directions. Like coma, it is really a secondary effect due to spherical aberration of oblique pencils.

Curvature of Field.—This term implies that correction has been applied sufficiently accurately to give, on a single focal surface, sharply defined point-images, but that this focal surface is curved. Since it is necessary to use plane surfaces in photography, this curvature must be made as small as possible, and a flat field produced.

Distortion of an object is shown in the illustration (fig. 9). In a simple lens distortion is primarily a consequence of spherical aberration. The use of a diaphragm reduces it. Barrel-shaped distortion is increased by a stop in front of the lens, pin-cushion distortion by one behind the lens. It is remedied generally by placing the diaphragm between two compound lenses, so that the distortion effects neutralize each other.

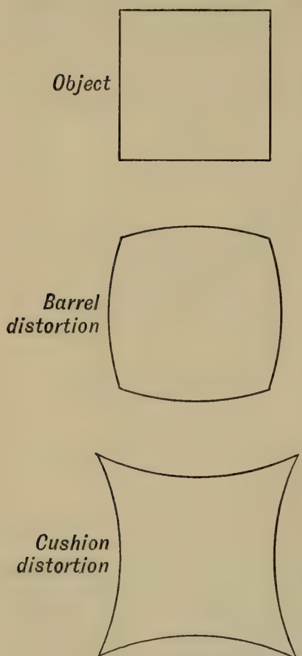


Fig. 9.—Illustrating Image Distortion

Aperture and Depth of Focus.—In the foregoing discussion, the relation of the diaphragm-aperture to aberration and definition has been merely outlined. We may note that, since photographs have to represent by an image in one plane an object in three dimensions, it is necessary that object-points at varying distances from the camera should be capable of reproduction in good definition. The manner in which a small aperture or "stop" helps this *depth of focus* is illustrated in the diagram (fig. 10). Assuming an object-point to be reproduced as an image-disc, there will be a limiting size which the disc must not exceed.[1] Suppose the diameter of this to be pq, $p'q'$ (fig. 10), then it is evident that the smaller the aperture the greater is the *depth of focus*, measured by the interval marked x in the figure.

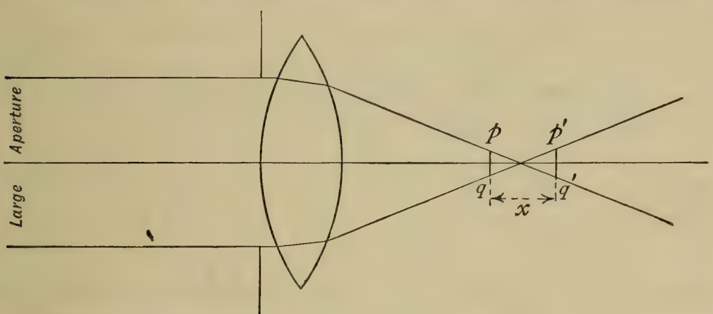
Aperture and Intensity of Illumination of Image.—The ratio (diameter of stop/focal length of lens) is called the *f/ratio of the lens*. The intensity of illumination of the image formed by

[1] Called "the circle of confusion"; a circle with a diameter of $\frac{1}{250}$ of an inch represents average critical definition.

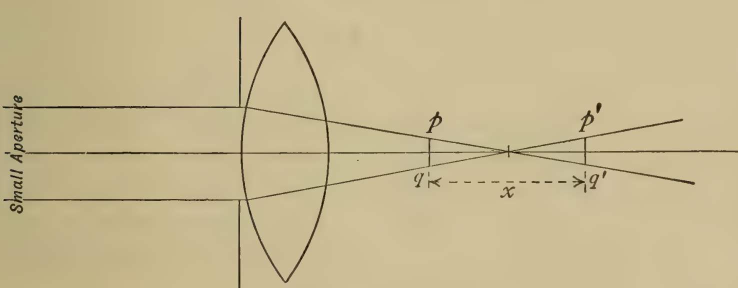
the lens is proportional to the square of this ratio for distant objects.

Let δs be a small area on the object-plane (fig. 5), i the intensity of illumination of the object-plane, then $i\delta s$ measures the radiant energy leaving the surface in the right-hand direction.

The part of this energy caught by the lens with its stop is $i\omega\delta s$, where



Showing Effect of Aperture on Depth of Focus



Illustrating Effect of Aperture on Depth of Focus

Fig. 10

ω is the solid angle subtended by the lens-opening at the area δs. This energy is spread over the image corresponding to δs, i.e. over an area δS, say, so that the intensity of illumination of the image i' is

$$i' = \frac{i\omega\delta s}{\delta S}.$$

Now the average solid angle subtended at points on the object-plane is

$$\frac{\pi d^2}{16\pi u^2} = \frac{d^2}{16u^2},$$

where d is the stop-diameter, and u the object-distance; and $\delta s/\delta S = \frac{u^2}{v^2}$, where v is the image-distance.

$$\therefore\ i' = i\frac{d^2}{16u^2}\frac{u^2}{v^2},$$

i.e. $i' \propto \frac{d^2}{v^2}$, i.e. $\propto \frac{d^2}{f^2}$ for distant objects, when v is nearly equal to f.

For convenience, stops are usually marked with the f/ratio, since the length of exposure necessary with a given plate is proportional to the intensity of illumination of the image formed by the lens. Thus, for example, we may have the series:

Stop numbers ..	$f/4$	$f/5{\cdot}6$	$f/8$	$f/11$	$f/16$	$f/22$	$f/32$
Exposure ..	1	2	4	8	16	32	64

Neglecting losses by absorption and reflection, these values define the "speeds" of lenses, and are often defined as the measures of the *rapidity* of the camera. Such losses, however, may amount to between 20 and 50 per cent in ordinary objectives, since each pair of surfaces means a loss of some 10 per cent by reflection. The absorption-loss is usually negligible for visible light, but scatter- and double-reflection from uncemented surfaces may considerably reduce "contrast", and, when concentrated, produce "flare" spots.[1] Objectives working from $f/2$ to $f/5$ are high-speed lenses, from $f/5$ to $f/8$ medium, above $f/8$ slow. In general it may be noticed that *covering-power* (angle of view) and *definition* have to be sacrified to secure high speed, and speed sacrificed to secure good covering-power, i.e. uniform definition over a large flat field.[2]

The *angle-of-view* may be defined as the angle between the extreme coplanar rays entering the camera. If α be this angle, its normal magnitude is given by the rule

$$\tan\frac{\alpha}{2} = \tfrac{1}{2}\left(\frac{\text{longer edge of plate}}{\text{focal length of lens}}\right).$$

If α is less than 45°, the lens is of a narrow angle; from 45° to 70°, normal; above 75°, *wide angle*. See Chapter III, p. 76.

[1] For accurate data on this, see the recent book by E. Goldberg, *Der Aufbau des photographischen Bildes*, Chapter III, pp. 23–43. W. Knapp, Halle, 1922.

[2] See Chapter III, p. 73 *et seq*.

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CHAPTER III

Photographic Optics

Photographic Images and Objectives.—The subject will be treated from the point of view of the user of photographic lenses, and not from that of the optical designer. The mysteries and intricacies of optical computation will therefore not be dealt with at all, and the theory will be restricted to those parts which are required for a proper understanding of the formation of images, of their perspective and sharpness, and of the limitations imposed partly by aberrations and partly by the very nature of light.

Photographic objectives are required to produce flat pictures of the objects photographed as faithfully as possible by the action upon a sensitive plate of the light-rays sent out by those objects. We must therefore begin by defining what is a faithful rendering.

The Ideal Image.—In most cases, the objects to be depicted are three-dimensional, and as the greater includes the less, we shall secure the broadest foundation of our inquiry by assuming that a scene including objects of all kinds and at all distances is to be represented as faithfully as possible on a flat surface. Supposing that we have such a scene in front of us and that we move about, we immediately notice that it looks different from every point of view which we may take up. A near object which from one viewpoint appears superposed upon a particular feature in the background covers some other distant object when we move a little. Evidently we cannot show the near object in both positions (and in all intermediate ones) in a single picture, and by following up this simple observation to its ultimate logical conclusion we become convinced that a perfectly truthful rendering of the scene is only possible if we fix the point of view absolutely.

We therefore decide to set up a screen with a small pin-hole occupying and fixing the selected point of view. Looking through

this pin-hole, we shall see any near object in a perfectly definite position with reference to the background, and we shall have a definite, sharply defined scene capable of being drawn upon a single surface.

If we now place a transparent drawing surface, say a sheet of flat glass, between the objects to be depicted and the pin-hole and take up a pointed drawing instrument, let us say a writing diamond, we shall have no difficulty, on looking through the pin-hole, in tracing the scene, point for point and line for line, as it appears projected upon our drawing surface, and if we imagine light and shade and colour also filled in, it is self-evident that the complete drawing

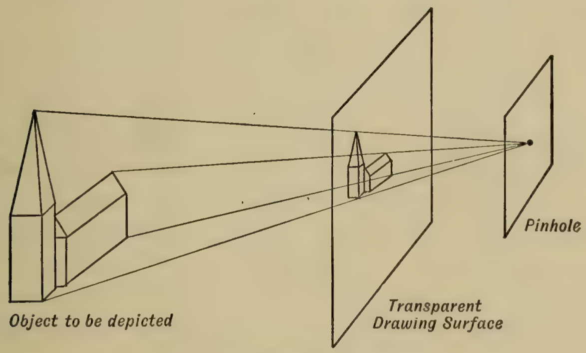


Fig. 1

represents as truthful a rendering of the whole scene as could be desired, for every point and line of it accurately covers the corresponding feature of the real objects and displays the relations of the latter, as seen from the selected point of view, with absolute precision.

This image we therefore accept as our ideal of perfect perspective, and as the standard with which a photograph taken by a lens from the same point of view and to the same scale should be compared. Our drawing will have the property of covering the scene, point for point and line for line, however the drawing surface may be placed; that is, whether it is placed in a vertical position or at any angle; from the purely geometrical point the perspective will always be correct. But as by ancient convention natural scenes are always drawn as they would appear when projected upon a vertical drawing surface, we become used from infancy to this particular perspective, and any departure from it is felt to be intolerable; for that reason verticality of the drawing surface becomes a conventional addition

to the definition of correct perspective, but there is no geometrical or logical justification for the restriction.

The likeness between our drawing and the reality it represents depends only on one fundamental assumption, namely, on the rectilinear propagation of light, which is in fact the basis of our idea of a straight line. Barring the minute Einstein effect, which causes a faint curvature of rays of light passing close to a huge mass like the sun, the straightness of light-rays still remains, and no doubt always will remain, the sure foundation of nearly all measurements of distances and relative positions, and we may safely accept it as an abundantly established fact. It immediately leads to an extension of the process of image formation illustrated in fig. 1. The drawing there shown could not be produced photographically on a sensitive plate, for if the latter were substituted for our sheet of glass, it would merely receive uniform illumination from all the world in front of it, and would be hopelessly solarized in a fraction of a second. But the light-rays proceeding from the various points of the landscape towards our pin-hole, which our eye enabled us to single out by placing the drawing point at the point of the drawing surface which covered the corresponding point of the landscape, will go on along their absolutely straight paths through the pin-hole, and they will then be isolated and secure from being swamped by the intense general illumination in the open space to the left of the pin-hole. Consequently only those rays by which we traced our drawing will pass into the space to the right of the pin-hole, and if we place a light-tight box behind the latter and expose a sensitive plate to the rays coming through the pin-hole, we shall have the proper conditions for the production of a latent image.

If we now refer to fig. 2, showing the transparent drawing surface of fig. 1 to the left of the pin-hole and the sensitive plate to the right of it, it is at once obvious that the crossing of all the effective rays in the pin-hole will cause an inverted image to be produced on the sensitive plate; but if the latter is placed so as to be exactly parallel to the original drawing surface, then this inverted image on the sensitive plate will, by simple propositions of solid geometry, be exactly similar to the drawing; that is, every angle like that of the two arms of the L in fig. 2 will be accurately reproduced, and every length will be depicted on the sensitive plate enlarged or diminished in the exact ratio of the distance f' from the pin-hole to the sensitive plate to the distance from the pin-hole to the original drawing. The inverted picture on the sensitive plate will therefore

be just as faithful a rendering of the actual three-dimensional scene as the drawing, which, as will now be realized, was considered and discussed merely because it supplies the most direct evidence of the possibility of a flat picture which when viewed from the correct point of view will accurately cover every point and line in any subject. The transparent drawing was our *pons asinorum*.

It should be noted that the image of the L which is obtained on the sensitive plate will appear merely inverted only if we look at the negative from the right of fig. 2, that is, from the side opposite that on which the pin-hole is, or, in photographic language, through the glass-side of the negative. If we look at the negative from the

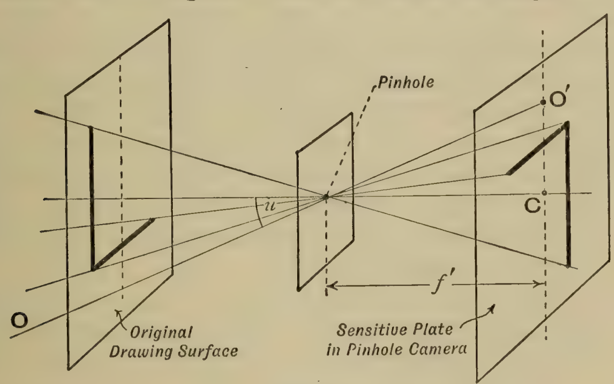


Fig. 2

side of the pin-hole, we shall see the L as in a looking-glass. This effect crops up in certain ferrotype photographs taken direct, and also accounts for the need of a reversing prism in certain photomechanical processes in which the final printed picture has the film-side orientation.[1]

Characteristics of the Pin-hole Image.—As we shall use the pin-hole image as our standard of perfect perspective, with which the images yielded by lens-systems are to be compared, we must put its characteristic properties into a convenient and precise form suitable for such comparisons.

A very convenient and perfectly reliable test can be based directly upon our principal deduction from fig. 2, namely, upon the perfect similarity in the strict Euclidian sense of the image obtained on a plate which is parallel to a plane diagram. If we prepare an accurate and flat test-diagram, which may consist merely of two sets of parallel

[1] See p. 459.

and equidistant straight lines crossing each other at right angles, the image should display a perfectly corresponding arrangement. Hardly any photographic lens will bear this test if it is carefully carried out. In order that the test be perfectly fair, great care must be taken in ascertaining that the test-diagram is accurately drawn on a truly flat surface, that the sensitive plate employed is also truly flat, and that it is placed parallel to the test-diagram. The last condition can be relaxed if the test of the negative is limited to testing lines in all available positions merely for straightness, for it follows from the complete theory of lenses that a lens which renders *any* straight line as a straight-line image must yield correct perspective.

A more mathematical test, which is the most convenient one for designers of lenses and in scientific applications such as photographic surveying, can also be taken from fig. 2. If a distant object is located in a direction forming an angle u with a perpendicular dropped from the pin-hole upon the sensitive plate, and if the distance from the pin-hole to the sensitive plate is f', then the distance from the image O′ to the foot of the perpendicular C should measure $f' \tan u$ for any value of the angle u.

A third test which can frequently be conveniently applied to ordinary negatives is based on the following reasoning: If there is a straight line in the field of view in any orientation whatsoever, excepting a direction towards the pin-hole itself, then the rays passing from different points of it to the pin-hole will all lie in a true plane, for a straight line and a point outside that line (our pin-hole) define a plane. On emerging from the pin-hole these rays will spread out again in the same plane, and as the sensitive film is also a plane, the rays will cut the film in a straight line, for the intersection of two planes represents a straight line. Hence in a pin-hole image, and in any image formed by a lens giving correct perspective, any straight line is rendered as a straight-line image, quite regardless of the orientation of the object-line.

A heavily loaded plumb-line is a convenient object for this test. The natural sea horizon is *not* straight; it has the curvature of the earth, and from a high viewpoint this is extremely obvious even to the unaided eye.

In images produced by lens-systems, departures from the correct perspective yielded by a pin-hole are usually referred to as *distortion*. Lens-systems which are free from distortion are frequently described as " rectilinear " because, as was shown above, they render every

straight line in the objects photographed as a perfectly straight line in the flat image.

Our definition of correct perspective, which is the only one capable of exact geometrical formulation, rests on the criterion that the image, when placed at the proper distance f' from the selected point of view and into a position parallel to that of the sensitive plate on which the negative was produced, will cover the scene point for point and line for line. According to this definition, every pin-hole image and every image produced by a rectilinear or non-distorting lens-system has correct perspective. Our definition thus appears to be incompatible with many well-known types of photographs taken with excellent lenses, the perspective of which is described by all kinds of uncomplimentary adjectives, such as false, violent, misleading, or unnatural. Pictures of buildings with converging or diverging vertical lines, portraits with a huge nose, steeply receding chin and forehead and diminutive ears, cramped steamer-cabins which are made to appear as spacious bedrooms, are familiar examples. All these productions, when viewed from the correct distance f' and *held at the angle at which the sensitive plate was exposed*, at once take on a perfectly natural appearance, thus proving that the perspective is not wrong but merely unusual or unconventional, and ill-adapted to our usual way of looking at pictures. *To secure the conventional and pleasing representation of buildings and tall natural objects, the sensitive plate must be in an accurately vertical position and not tilted.* In portraits we assume that they represent the original as seen from a distance of 10 feet or more; the unnatural appearance results when the lens is placed within a few feet or even less of the victim. The misleading effect of photographs of steamer-interiors is due to the use of wide-angle lenses; the pictures produced by painters and artists hardly ever embrace an angle of more than 30° or 40°, and accustom us to viewing pictures from a distance yielding a subtense not exceeding that angle. For that reason photographs covering a much larger angle never give a correct impression. As most people cannot see distinctly objects at a distance less than 8 or 10 in. from the eye, all pictures taken with a lens of a focal length below this minimum cannot be viewed from the proper distance, and therefore never look right until they are enlarged or magnified optically. That is the heavy penalty attached to snapshots taken by small cameras. It will thus be seen that the unsatisfactory types of photographs, whose perspective is usually condemned, are due to offences against well-established and

thoroughly justifiable artistic conventions; the proper application of these conventions naturally is left to the user of photographic lenses. The designer can only render the perspective geometrically correct according to the criteria deduced above; when he designs a wide-angle lens, he knows perfectly well that the vast majority of the images (they can rarely be called pictures!) produced by them will be caricatures of the original subjects, but he has to meet a demand and does his best.

Panoramic Pictures.—This section cannot properly be concluded without reference to an unusual type of photographic image, namely, true panoramic pictures. These represent an attempt to avoid the strained perspective of wide-angle views taken on a flat plate by bending the latter—practically always a film—into the shape of a cylinder which has its axis passing through the point of view from which the view is taken. If lens and camera are correctly designed, the resulting picture will cover the scene taken point for point and line for line when again bent into the original cylindrical form and viewed from the original point of view. When so viewed the perspective of a panoramic photograph is perfectly correct, and when greatly enlarged and mounted on the cylindrical wall of a suitable building such a picture becomes highly realistic and impressive. But it is the fate of most of these panoramic photographs to be mounted flat and in the original very small size. Under these conditions the effect is rarely satisfactory, and becomes grotesque if a long building is taken, for all the horizontal lines, which by the accepted conventions ought to be straight, then come out with a pronounced curvature.

Shortcomings of the Pin-hole Image.—The perfect perspective of the pin-hole image, which can only be approached but can never be fully attained by even the most carefully designed lens-system, is accompanied by two drawbacks of such severity as to render the regular use of pin-holes instead of lenses practically impossible. These drawbacks are the extremely low intensity or brilliancy of the image and its imperfect sharpness. From the point of view of geometrical optics it would appear as if the image could be rendered as sharply defined as might be desired by making the pin-hole small enough, for a very minute pin-hole would allow only a single ray from each object-point to reach the plate, and the image should therefore also be a sharp point.

It is one of the most important facts in support of the undulatory or wave-theory of light that experiment does not bear out this geo-

metrical conclusion. If we try a succession of pin-holes of diminishing aperture on any one camera-extension, we easily ascertain that, whilst at first there is a steady gain in sharpness, this comes to an end with some particular small aperture, and if we try still smaller pin-holes the image deteriorates again and becomes hopelessly blurred with a very minute aperture. Moreover, the aperture which gives the sharpest image at one camera-extension does not do so when the extension is made decidedly longer or shorter; there is a different optimum size for each extension. The wave-theory of light explains these strange results by the interference of the light which reaches the neighbourhood of the geometrically ascertained image-point through different parts of the pin-hole aperture. The theory is fully explained in treatises on physical optics;[1] we will therefore merely state the result that the best aperture A of a pin-hole for use on reasonably distant objects with a camera length f' is found, for inch-measure, by the approximate formula

$$A^2 = 0{\cdot}00007 \times f'.$$

This gives for

f' =	3″	4″	6″	10″
A =	0·″014	0·″017	0·″020	0·″026
f/ratio =	f/200	f/230	f/300	f/385

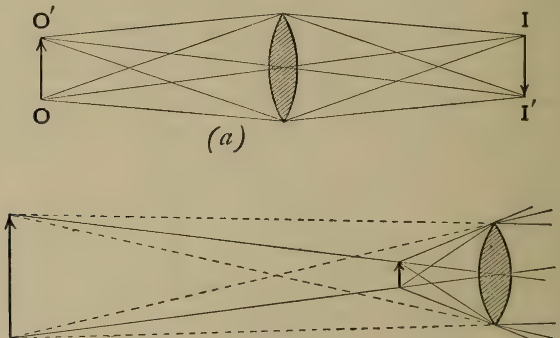
The " rapidity " or f/number corresponding to these apertures has been added in a third line, and when it is borne in mind that with average light, plate, and open-air subject about one second's exposure is required at (say) f/22, and that the exposure increases with the square of the f/number, it will be realized that pin-hole exposures nearly always run into minutes, and may reach many hours in indoor photography. The wave-theory enables us also to estimate the sharpness of the image; with the respective best apertures stated in our little table the image of a point would measure about 0·004 in. at 3-in. camera-extension, about 0·006 in. at 6-in. extension, and about 0·008 in. at 10-in. extension.[2] These figures come close to those realized by good lenses in the outer part of their field of view, and account for the fact that well dimensioned pin-holes can compete with lenses as regards definition when a field of wide angle is to be covered. It is remarkable and should

[1] Wood's *Physical Optics*.

[2] The calculation is based on the formula for the diameter of the spurious disc given subsequently, page 81

be noted that the size of the image calculated by the wave-theory is in every case less than one-third of the diameter of the pin-hole. Geometrically the image would be—for distant objects—a kind of shadow of the pin-hole, and therefore would have the diameter of the pin-hole. The undulatory theory therefore leads to a much sharper image than could be expected by geometrical reasoning. This is a practically constant result of the application of the much-maligned "diffraction theory" to optical problems.

General Properties of Lenses.—As every book on physics or optics deals more or less adequately with the elementary properties of lenses and lens-systems, we will assume it to be known that a



(a)

(b)

Fig. 3

convex lens, or a system of lenses which has properties similar to those of a simple convex lens, refracts the rays of light which are sent out by an object OO′ so as to produce either a real inverted image II′ (fig. 3*a*), or a virtual and erect image (fig. 3*b*). The first case is realized by every camera-lens, the second by any ordinary magnifying glass. There is an infinitely improbable special case of an object placed exactly at the principal focal point, for then all the rays from any one point of the object would emerge as a parallel bundle, and no image would be produced at any finite distance.

The characteristic property of a lens is thus, that with the one exception just mentioned all the rays received from an object-point are so refracted as to meet again in the corresponding or "conjugate" real image-point, or, in the case of a virtual image, so as to appear to come from the conjugate virtual image-point. Important conclusions can be drawn from this, and although they are extremely

simple and obvious they require strong emphasis, because many doubts and difficulties are simply due to the fact that these conclusions have not been duly appreciated, or at any rate have not become real living knowledge ever present to the mind. *The first of these conclusions is that, as every ray which passes from an object-point through a lens or system must pass through the conjugate image-point, any single ray traced through is a geometrical locus, in Euclid's sense, of the image-point, and thus narrows down the search for the latter.* The second and supplementary conclusion is that *two rays starting from the object-point in different directions are sufficient to locate the image-point quite definitely*, for as the latter must lie on both rays, it can only be found at their intersecting point. All the convenient graphical methods of finding the image depend on these conclusions. With lens-systems which give sensibly imperfect images, the result will naturally vary according to which two rays are selected, but the consequent uncertainty can only be of the same order as the spurious diameter of the complete image of a point, and is therefore not serious.

Another general property of lenses and lens-systems which should be thoroughly realized and assimilated is that any system will form images of every object within its range and even of its own constituent parts. Some of these images play an important part in the theory, and others can become a source of grave trouble in the practical use of a lens. The *flare-spot* and *ghost-images* are examples to be referred to subsequently.

Theory of Perfect Lens-systems.—The general relations between object and image are usually worked out on the basis of the Gaussian theory; the validity of this theory is restricted to a very small aperture and a very small field of view, or to what is usually called a threadlike or capillary space around the optical axis of a lens-system. Abbe, the famous collaborator of Carl Zeiss of Jena, succeeded in finding a purely geometrical treatment of the problem which is free from restrictions up to a certain point, and as the Abbe form of the general theory of lenses leads to many important general conclusions, we will adopt it.

In elementary optics it is shown that any centred lens-system will give geometrically perfect images of correct perspective if the aperture is small enough and the field sufficiently restricted. As modern photographic objectives demonstrate, it is possible by skilful choice of glass and of lens-forms to secure these properties with a considerable aperture and for a field of very considerable angular

extent. At the present time it is therefore not such a far-fetched assumption as it would have been 80 years ago, when Gauss framed his theory, to postulate the possibility of perfect lens-systems, defining these as follows:

A perfect lens-system is one which will depict objects situated in any plane at right angles to its optical axis in a conjugate image-plane also at right angles to the optical axis, with perfect definition and with perfect freedom from distortion.

Put into ordinary photographic language, this definition means that a flat test-diagram is to yield a perfectly sharp image on a flat focusing screen, *and* that this image shall be a reduced or enlarged replica of the test-diagram and geometrically similar to it.

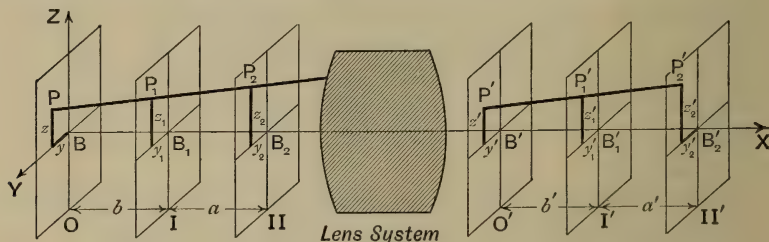


Fig. 4

We can then prove the remarkable theorem that *a lens-system will be perfect for objects at any distance if it is perfect for objects at only two different distances.*

With reference to fig. 4, it is assumed that the lens-system indicated is known to give perfect images of objects in a plane I placed at right angles to the optical axis and cutting the latter at B_1, the images being produced in the conjugate plane I′, which is at right angles with the optical axis at B_1', and that the same relations exist between the planes II and II′. Using solid co-ordinate geometry, the distance from plane I to plane II, i.e. B_1B_2, shall be a, the distance from plane I′ to plane II′, i.e. $B_1'B_2'$, shall be a', both being known.

The linear magnification of the images in I′ shall be M_1', which means that a point P_1 in plane I, fixed by the co-ordinates y_1 and z_1, is depicted at P_1' with the co-ordinates $y_1' = y_1M_1'$ and $z_1' = z_1M_1'$. Correspondingly the magnification in II′ shall be M_2', so that a point P_2 in plane II, with co-ordinates y_2 and z_2, is depicted at P_2' with the co-ordinates $y_2' = y_2M_2'$ and $z_2' = z_2M_2'$. The magnification numbers shall be positive for an erect image (as

shown in the "all-positive" diagram), negative for an inverted image; they will be larger than one for an image larger than the corresponding object, and fractional for an image which is smaller than the corresponding object. We only stipulate that M_1' and M_2' shall both be finite numbers, and that they shall not be equal.

We now consider a new object-plane O, also at right angles to the optical axis, which it cuts at B; the distance from O to I, i.e. BB_1, shall be b. Let P, with the co-ordinates y and z, be any point in this new object-plane. A ray travelling from P to the lens-system must cut the two known object-planes I and II, say in points P_1 and P_2. For the co-ordinates of P_1 we can adopt the general symbols y_1 and z_1; but as a light-ray is an absolutely straight line, P_2 must lie on PP_1 produced, and its co-ordinates must be determined accordingly; they cannot be left in the general form y_2 and z_2. On account of the unvarying slope of a straight line, we conclude (and can prove easily by similar triangles) that as our ray has changed its y-co-ordinate by $(y_1 - y)$ in covering the distance b from O to I, its y-co-ordinate must change by $(y_1 - y)(b + a)/b$ on covering the distance $(b + a)$ from O to II; hence $y_2 = y + (y_1 - y)(b + a)/b = y_1(a + b)/b - ya/b$. Precisely the same conclusions apply to the z-co-ordinate; therefore $z_2 = z_1(a + b)/b - za/b$.

We can now locate our ray $P'P_1'P_2'$ in the image-space to the right of the lens-system, after it has passed through the latter, by the following universally valid argument: As the ray passes through P_1 it may be looked upon as identical with one of the rays which P_1 itself would send out, and as P_1 is known to be sharply depicted in plane I′ under magnification M_1', our ray must cross this plane with the co-ordinates $y_1' = y_1M_1'$ and $z_1' = z_1M_1'$.

By the same argument our ray may also be regarded as identical with one from P_2, and must therefore cross plane II′ with the co-ordinates $y_2' = y_2M_2'$ and $z_2' = z_2M_2'$, or on introducing the previously determined values of y_2 and z_2, at

$$y_2' = M_2'[y_1(a + b)/b - ya/b] \text{ and } z_2' = M_2'[z_1(a + b)/b - za/b].$$

We have thus located two points of the emerging ray which is conjugate to the ray PP_2, and as two points definitely determine a straight line and therefore also a ray of light, we known the entire course of the emerging ray. We can therefore determine the point at which the emerging ray cuts through any normal plane in the image-space. Let O′ be such a plane, the distance $B'B_1'$ from it

to the known plane I′ being b'. We apply the argument of the uniform slope of the ray and obtain the proportions

$$(y_1' - y')/b' = (y_2' - y')/(b' + a')$$
$$\text{and } (z_1' - z')/b' = (z_2' - z')/(b' + a'),$$

which are easily transposed into the form

$$a'y' = y_1'(a' + b') - y_2'b',$$
$$a'z' = z_1'(a' + b') - z_2'b'.$$

As all the equations for the z-co-ordinate differ from those of the y-co-ordinate only by having z in the place of y, we need only carry out the remainder of the transformations for one co-ordinate, and we will choose y. Putting in the values of y_1' and y_2' already determined above, we obtain on slight simplification

$$y' = y\mathrm{M}_2'b'a/a'b + (y_1/a')[\mathrm{M}_1'(a' + b') - \mathrm{M}_2'b'(a + b)/b].$$

This equation shows that the point P′ at which the emerging ray cuts through an arbitrarily placed plane O′ depends on the distance y_1 at which the entering ray passes through plane I; and as an exactly corresponding equation results for z', it follows that every ray from the object-point P cuts O′ in a different point. No sharp image is therefore formed in this plane if it is placed at an arbitrary distance from the lens-system. We could not reasonably expect any other result, for every tyro knows that if a camera is racked out to some arbitrary length it is highly improbable that a sharp image of any particular object should result. But we can immediately draw a decisive conclusion from our equation, for the effect of variations of y_1 (and also of z_1) depends on the factor in the square bracket. As this bracket contains a linear function of b', there must be one, and only one, particular value of b' for which the factor becomes zero, and for which y_1 and z_1 have no effect on the value of y' and z', so that a perfectly definite point P′ results, through which all rays from P must pass. That evidently is the sharp focus of P. Putting the expression in the square bracket equal to zero and solving for b', we find

$$b' = a'\mathrm{M}_1'/[\mathrm{M}_2'(a + b)/b - \mathrm{M}_1'], \ldots\ldots\ldots(1)$$

and as the second term of the equation for y' disappears for this value of b', we now have

$$y' = y\mathrm{M}_2'b'a/a'b,$$

and on introducing the special value of b'

$$y' = y\frac{a}{b}\,\frac{M_1'M_2'}{M_2'(a+b)/b - M_1'}, \quad \ldots\ldots\ldots\ldots(2)$$

with a corresponding equation which determines

$$z' = z\frac{a}{b}\,\frac{M_1'M_2'}{M_2'(a+b)/b - M_1'}.$$

Obviously y'/y is equal to z'/z, and both represent the linear magnification M′ at which objects in plane O are depicted in the conjugate plane O′ as determined by equation (1). Therefore

$$M' = \frac{a}{b}\,\frac{M_1'M_2'}{M_2'(a+b)/b - M_1'}. \quad \ldots\ldots\ldots\ldots(3)$$

The equations (1), (2), and (3) contain the complete proof of Abbe's remarkable theorem that a lens-system which is perfect for objects in two normal planes of the object-space at a finite separation is equally perfect for object-planes at any distance, for by equation (1) there is for an object-plane O at any distance b from our plane I a conjugate image-plane O′ at distance b' from plane I′ in which any point O is sharply depicted, and by equations (2) and (3) the images so formed are not only sharp, but also have a perfectly fixed magnification M′, and are therefore free from distortion.

Our three equations contain far more than this extremely valuable general information. We can easily extract from them all the fundamental points and data of a lens-system. The two most characteristic planes are those in which objects at a very great distance from the lens-system are focused; they are known as *the principal focal planes*, and the points at which they cut the optical axis are called *the principal or infinity foci.* The *principal focus in the* object-space is called *the first or anterior focal point*; that in the image-space, *the second or posterior focal point.* We can locate both by discussion of equation (1). For objects in a plane O at a very great distance to the left of the lens-system b will grow beyond all measure. It occurs on the right of the equation in the form $(a + b)/b = a/b + 1$, and as a has been specified as finite, a/b will become small and insignificant compared to 1 when b becomes very large. Calling the special value of b' for very distant objects b'_f, we therefore have the distance from the posterior principal focus to plane I′ defined by

$$b'_f = a'M_1'/(M_2' - M_1'). \quad \ldots\ldots\ldots\ldots(4)$$

On the other hand, O will become the anterior focal plane when the conjugate plane O′ moves to a very great distance; the anterior focal plane is therefore found by postulating that equation (1) shall yield a huge value of b'. As a' and M_1' have both been specified as of finite magnitude, this can only be brought about by a zero-value of the denominator on the right of (1). The condition therefore is

$$M_2'(a + b)/b = M_1',$$

and if we solve this for b and call the special value b_f because it fixes the distance from the anterior focal plane to plane I, we find

$$b_f = -\, aM_2'/(M_2' - M_1') \ldots\ldots\ldots\ldots\ldots (5)$$

The two principal foci defined by (4) and (5) are very easily determined for any lens-system of the type to which photographic lenses belong; we have only to turn the lens-system towards a distant object and to find its sharp image in the two positions—front lens towards the distant object and back lens towards the object—in order to locate them. The two principal foci are therefore the most natural points from which the distances of objects and images may be measured, and they have the additional merit of leading to the simplest possible formulæ for the relations of object and image. These formulæ are easily obtained by combining equations (4) and (5) with the general equations (1) and (3), which are valid for objects at any distance and for any magnification M′. Equation (4) gives the distance from the posterior focus to the original plane I′, and equation (1) gives the distance from any image-plane to plane I′. Therefore the distance from the posterior focus to any image-plane is the difference or $(b'_f - b')$. Calling this distance X'_f, we therefore have

$$X'_f = b'_f - b',$$

and on putting in the values by (4) and (1) and bringing to a common denominator

$$X'_f = \frac{a'M_1'}{M_2' - M_1'} - \frac{a'M_1'}{M_2'(a+b)/b - M_1'}$$

$$= \frac{a'M_1'M_2'(a + b)/b - a'M_1'M_2'}{(M_2' - M_1')(M_2'(a + b)/b - M_1')},$$

which becomes, on simplifying the numerator and then factorizing,

$$X'_f = \frac{a'}{M_2' - M_1'} \cdot \frac{M_1'M_2'a/b}{M_2'(a+b)/b - M_1'} = M'\left(\frac{a'}{M_2' - M_1'}\right),$$

the last by our equation (3).

For the distance X_f from the anterior focus to any object-plane we find by the same reasoning

$$X_f = b_f - b = -\frac{aM_2'}{M_2' - M_1'} - b.$$

Brought to a common denominator and then extended by $aM_1'M_2'$, this gives

$$X_f = -\frac{aM_1'M_2'}{M_2' - M_1'} \cdot \frac{M_2'(a+b) - bM_1'}{aM_1'M_2'} = -\frac{aM_1'M_2'}{M_2' - M_1'} \cdot \frac{1}{M'},$$

the last again by equation (3).

The equation for X'_f determines the distance from the posterior focus at which an image of magnification M' will be produced, as the product of M' and a factor $a'/(M_2' - M_1')$ which depends only on the fixed data of the system and is therefore constant. Similarly, the equation for X_f determines the distance from the anterior focus at which an object must be placed in order to secure an image of magnification M', and this distance is fixed as a constant, $aM_1'M_2'/(M_2' - M_1')$, divided by the desired magnification. The two equations therefore contain the complete and simple solution of the problem of the practical photographer: to determine the distances of object and image which will yield a prescribed enlargement or reduction.

The two constant factors are usually called the *equivalent focal lengths* of the lens-system; in order to obtain the conventional sign, they are defined thus:

For the image-space, to the right of the system,

$$f' = -a'/(M_2' - M_1'). \quad \ldots\ldots\ldots\ldots\ldots(6)$$

For the object-space, to the left of the system,

$$f = aM_1'M_2'/(M_2' - M_1'). \quad \ldots\ldots\ldots\ldots\ldots(7)$$

The equations for X'_f and X_f then take the form

$$X'_f = -f'M'; \; X_f = -f/M'; \; X_f X'_f = ff', \ldots . (8)$$

the third being obtained by simple multiplication of the first and second.

Experimental Determination of the Constants for any Lens-system.—The equations (4) to (7) are sufficient and highly convenient for the determination of the equivalent focal lengths and of the focal points of any lens-system, and equations (8) then serve to fix the positions of object and image which will realize any desired magnification.

1. *A Universally Applicable Method.*—We carry out exactly the measurements on which the preceding theory is based. Referring to fig. 5, we set up the camera before a test-diagram, or merely a scale

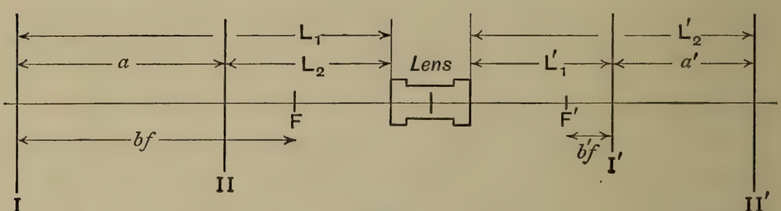


Fig. 5

at a distance which will give a diminished image, and sharply focus the latter. We then measure the distance L_1 from the diagram or scale to any suitable permanent mark on the lens-mount (its endface is assumed to have been selected in the diagram), and the distance L_1' from the same or some other convenient and permanent mark of the lens-mount to the focusing screen.

We further note the size of image yielded by an object of known size, and by division find the (fractional) magnification M_1'. By way of numerical example we will take $L_1 = 34{\cdot}0$ in., $L_1' = 7{\cdot}74$ in., and assuming that a length of 10 in. in plane I has yielded an image measuring 2·20 in. on the focusing screen, we have $M_1' = -2{\cdot}20/10 = -0{\cdot}220$ times. The minus-sign is necessary because the image is an inverted one.

We then bring the camera closer to the object (or vice versa), which now acts as plane II of the theory, and measure L_2 and L_2' and the new magnification M_2'. We will assume that the results are $L_2 = 9{\cdot}51$ in., $L_2' = 18{\cdot}0$ in., and, if 3 in. in the object-

plane have yielded an image measuring 5·70 in., $M_2' = -5{\cdot}70/3 = -1{\cdot}90$. We then have the distance

a of the theory $= L_1 - L_2$, or
$a = L_1 - L_2 = 34{\cdot}0 - 9{\cdot}51 = 24{\cdot}49$;
the distance $a' = L_2' - L_1'$, or
$a' = L_2' - L_1' = 18{\cdot}0 - 7{\cdot}74 = 10{\cdot}26$;
and the magnifications $M_1' = -0{\cdot}220$, $M_2' = -1{\cdot}90$.

By (6) we then calculate

$$f' = -a'/(M_2' - M_1') = -10{\cdot}26/(-1{\cdot}90 + 0{\cdot}22) = 10{\cdot}26/1{\cdot}68,$$
$$\text{or } f' = +6{\cdot}11 \text{ in.}$$

By (7) we obtain

$$f = aM_1'M_2'/(M_2' - M_1') =$$
$$24{\cdot}49 \times (-0{\cdot}22) \times (-1{\cdot}90)/(-1{\cdot}90 + 0{\cdot}22),$$
$$\text{or } f = 10{\cdot}23/(-1{\cdot}68) = -6{\cdot}09 \text{ in.}$$

It will be shown presently that it is not an accident that the two focal lengths have come out very nearly numerically equal but of opposite sign; they must do so, and this forms a useful check on the measurements, for there must be an error in the latter or in the calculations if the two focal lengths come out sensibly different from each other.

To complete the determination of the constants, we must locate the two principal focal points by (4) and (5). By (4) we calculate the distance from the posterior focus F′ to image-plane I′, and find

$$b'_f = a'M_1'/(M_2' - M_1') = 10{\cdot}26 \times (-0{\cdot}220)/(-1{\cdot}68) = +1{\cdot}34 \text{ in.}$$

I′ therefore lies 1·34 in. to the right (on account of the positive sign) of F′, and as L_1' was 7·74 in., F′ lies at $7{\cdot}74 - 1{\cdot}34 = 6{\cdot}40$ in. to the right of the mark from which L_1' was measured, and if the focusing screen were adjusted to that distance, very distant objects should be found exactly in focus. The anterior focus F is similarly located by (5):

$$bf = -aM_2'/(M_2' - M_1') = -24{\cdot}49(-1{\cdot}90)/(-1{\cdot}68) = -27{\cdot}7 \text{ in.}$$

Plane I therefore lies 27·7 in. to the left of F, and as L_1 was 34·0 in., F lies at $34{\cdot}0 - 27{\cdot}7$ or 6·3 in. to the left of the mark to which the distances of I and II were originally measured.

2. *A Simplified Method* which avoids practically all of the calculations. We begin by determining F′ directly, for which purpose

we have only to find the sharp focus of a very distant object. With the above lens it should be found at 6·40 in. from the mark adopted for the image-space, and we will assume this figure. We then seek that distance L of the object from the mark employed for the object-space which yields a sharp inverted image of exactly natural size, or $M' = -1$ at a measured distance L' from the mark employed for the image-space. Suppose that this experiment had been carried out and had yielded $L = 12{\cdot}40$ in. and $L' = 12{\cdot}50$ in. By the first of equations (8), the distance from the posterior focus at which magnification $M' = -1$ (i.e. a natural-size inverted image) is produced is

$$X'_f = -f'M' = -f'(-1) = f'.$$

f' is therefore equal to the amount by which the camera must be racked out in order to change from the focus of distant objects to the natural-size focus. As we located the former at 6·40 in. and the latter at $L' = 12{\cdot}50$ in., we have $f' = 12{\cdot}50 - 6{\cdot}40 = 6{\cdot}10$ in. Accepting the statement that f and f' must be numerically equal, we can then also locate the anterior focus, for by the second of (8) it must lie at a distance equal to the focal length from the object which yielded a natural-size image. As that distance was measured as $L = 12{\cdot}40$ in. to the left of the mark, the anterior focus must lie at $12{\cdot}40 - f' = 12{\cdot}40 - 6{\cdot}10 = 6{\cdot}30$ in. to the left of the mark.

It should be stated once for all that it is not possible to determine the equivalent focal length reliably even to one part in one thousand, nor the location of the principal focal points to 0·01 in., partly because we cannot find the sharpest image with absolute precision, and partly on account of residuals of aberration which are present in all real lens-systems, and which cause variations of the result with the chosen distances of the object, and even with the size of the image which is measured.

3. *Calculation of the Requisite Distances of Object and Image for Any Magnification.*—This follows from equations (8), which give the distance X'_f of the image from F' and the distance X_f of the object from F for any value of M'. To obtain the distances from the marks employed in the above examples, we have only to add the constant amounts deduced from the experiments. For photographic purposes we can safely ignore all signs and deal with positive numbers only. If f' is the equivalent focal length (6·10 in. in the numerical example), L_f the distance of the anterior focus from the mark

(6·30 in. in the example), and L'_f the distance of the posterior focus from its mark (6·40 in. in our example), then the distance L of the object from the mark on the object-side is calculated for any magnification M′ of the desired image as

$$L = L_f + f'/M',$$

and the distance of the focusing screen as

$$L' = L'_f + f'M'.$$

In our example the formulæ would be

$$L = 6{\cdot}30 + 6{\cdot}10/M' \quad \text{and} \quad L' = 6{\cdot}40 + 6{\cdot}10 \times M'.$$

Supposing we wanted to produce an enlargement of a negative to two and a half times its own size, we should calculate

$$\begin{aligned} L &= 6{\cdot}30 + 6{\cdot}10/2{\cdot}5 = 6{\cdot}30 + 2{\cdot}44 = 8{\cdot}74 \text{ in.} \\ L' &= 6{\cdot}40 + 6{\cdot}10 \times 2{\cdot}5 = 6{\cdot}40 + 15{\cdot}25 = 21{\cdot}65 \text{ in.} \end{aligned}$$

For a reduction of a plan to one-third of its natural size, we should find

$$\begin{aligned} L &= 6{\cdot}30 + 6{\cdot}10/0{\cdot}3333 = 6{\cdot}30 + 18{\cdot}30 = 24{\cdot}60 \text{ in.} \\ L' &= 6{\cdot}40 + 6{\cdot}10 \times \tfrac{1}{3} = 6{\cdot}40 + 2{\cdot}03 = 8{\cdot}43 \text{ in.} \end{aligned}$$

If we wanted to secure an image 4 in. high of a person measuring 6 ft., we should have

$$M' = 4 \text{ in.}/72 \text{ in.} = \tfrac{1}{18}.$$

Therefore

$$\begin{aligned} L = 6{\cdot}30 + 6{\cdot}10/(\tfrac{1}{18}) &= 6{\cdot}30 + 18 \times 6{\cdot}10 = 6{\cdot}30 + 109{\cdot}8 \\ &= 116{\cdot}1 \text{ in., or } 9 \text{ ft. } 8{\cdot}1 \text{ in.} \end{aligned}$$

It would not be worth while to calculate the camera-extension L′ as it will be only a little beyond the infinity focus, and readily found experimentally.

As a general rule it is best to calculate the *longer* distance and then to obtain a sharp focus experimentally. For enlargements, therefore, the distance of the image should be calculated, for reductions that of the object.

As the real accuracy of the calculations does not exceed one part in 500 at most, the slide-rule may be used to great advantage by those familiar with that invaluable tool.

Completion of the Theory of Perfect Lens-systems.—It has been shown in the preceding section that the equations (1) to (8) contain the complete solution of the problems of image-formation, although the principal planes which play a prominent part in the Gaussian theory have not even been mentioned. It was found that a perfect lens-system can produce any magnification, and that the positions of object and image which will yield any prescribed value of M′ are perfectly definitely fixed by the equations already deduced. *The Gaussian principal planes* are those two conjugate planes for which the magnification is precisely " one "; that is, any object in one of these planes is depicted erect and natural size in the other. We can therefore locate them by our general equations

$$X_f' = M'a'/(M_2' - M_1') \quad \text{and} \quad X_f = -\,aM_1'M_2'/M'(M_2' - M_1'),$$

by introducing for M′ the special value + 1, and it will be seen that the resulting values correspond to $-f'$ and to $-f$ respectively as

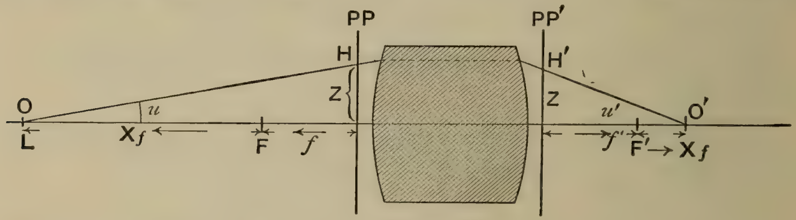


Fig. 6

defined in equations (6) and (7). Inasmuch as our special values of X'_f and X_f are measured from the focal points to the principal planes, whilst it is usual to measure the Gaussian equivalent focal lengths in the reverse direction, it will be seen that we were perfectly justified in defining f and f' in the form of equations (6) and (7), both as regards magnitude and also as to the sign.

The principal planes as conjugate planes of unit-magnification render it easy to draw another conclusion which is of very great importance. Let O on the optical axis be an object-point and O′ the conjugate image-point, let F be the anterior principal focus, PP the anterior principal plane, PP′ the posterior principal plane, and F′ the posterior focus (fig. 6). Any ray from O under an angle u with the optical axis must eventually pass through the conjugate image-point O′ under some definite angle u'. If the entering ray crosses the anterior principal plane at H, at distance Z from the optical axis, the ray may be looked upon as identical with a ray from

H, and as H is depicted in the conjugate posterior principal plane under "unit-magnification", the emerging ray must pass through a point H′ of PP′ also at distance Z above the optical axis. We seek a relation between the angles u and u'. Evidently we have

$$\tan u = Z/(f + X_f) \text{ and } \tan u' = Z/(f' + X'_f),$$

or by division,

$$\frac{\tan u}{\tan u'} = \frac{f' + X'_f}{f + X_f}.$$

If we call the magnification under which an object at O will be depicted at O′, M′, then we have by equations (8) $X'_f = -f'M'$ and $X_f = -f/M'$, and introducing these values into the last equation, it becomes

$$\frac{\tan u}{\tan u'} = \frac{f'}{f}\frac{1 - M'}{1 - (1/M')} = -\frac{f'}{f}M' \ldots\ldots\ldots (9)$$

As there are only constants on the right, it follows that in accordance with our theory all rays from O must reach O′ under such angles that $\tan u/\tan u'$ is a constant ratio, whatever value the angle u may have for any particular ray.

We now draw upon one of the most fundamental theorems in optics, which unfortunately cannot be proved here on account of its being deeply involved with both the theory of the aberrations of lenses and with the undulatory theory of light. We must therefore accept this theorem, which is known as *the optical sine condition*.[1] It states that a lens-system of any construction whatsoever cannot possibly be free from the grave defect to be described subsequently as *coma* unless it satisfies the condition

$$\frac{\sin u}{\sin u'} = \frac{N'}{N}M', \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

in which u, u', and M′ have the same significance as in our equation (9), whilst N stands for the refractive index of the medium *to the left* of the lens-system, and N′ for the refractive index of the medium to the right of the lens-system. The right side of (10) is therefore again an absolute constant for any given object-point O. We therefore have a demand by the inexorable sine-condition that the conjugate convergence angles u and u' must be in a constant ratio as to their sines, whilst by equation (9) they should be in a constant ratio

[1] See Monthly Notices of R.A.S., 1905, pp. 501–509, for complete treatment of this question.

as to their tangents. These two conditions are compatible for finite values of u and u' only in the one special case when $u = u'$, which can only be satisfied for one particular position of O and O′, *and therefore contradicts our demand that the lens-system shall be perfect for objects at all distances.*

As, on the one hand, the sine-condition is an immutable law of optics, and, on the other hand, our tangent-condition a logical deduction from the assumption that a lens-system could be rendered perfect for objects at two different distances, we are bound to conclude that this assumption (which in fact has never yet stood the test of severe experimental or computational trial) must be fallacious and untenable: *a perfect lens-system complying with our severe definition of perfection is impossible.* We can, however, draw several comforting further conclusions.

In the first place the clash between equations (9) and (10) arises from our assumption that the lens-system should be perfect for two different object-distances; therefore *we have no ground for denying the possibility of perfect correction for one distance only*, and this conclusion covers the vast majority of photographic lenses because they are only used on very distant objects, the images of which are formed close to the principal focal plane.

In the second place inspection of the parallel column of sines and tangents in any table of natural trigonometrical functions shows that for small angles *the difference between the sine and the tangent is minute*, and that it reaches $\frac{1}{4}$ per cent at about 4°. Now the demand as to sharpness of definition in photographic lenses is low compared to that expected from telescope- or microscope-objectives, and we may take it that as long as the angles u and u' are less than 4° the clash between our equations (9) and (10) may be treated as comparatively unimportant. That angle corresponds to a lens working at a " rapidity " of $f/7$ on the side of the shortest conjugate, and it is significant that this represents about the highest rapidity for which truly universal photographic objectives can be obtained.

If we now accept it that up to angles not exceeding 4° the sine- and the tangent-ratio may be treated as sufficiently nearly identical, we obtain a valuable equation by equating the right sides of the now harmonious equations (9) and (10), for this gives

$$-\frac{f'}{f}M' = \frac{N'}{N}M',$$

or

$$f'/f = -N'/N, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

and proves that there is a perfectly fixed and definite relation between the anterior and the posterior equivalent focal length of any lens-system of moderate aperture. For all photographic lenses we have air on both sides, and therefore $N = N'$. For photographic lenses we have therefore

$$f = -f', \quad \ldots\ldots\ldots\ldots\ldots\ldots(11^*)$$

that is, the equivalent focal lengths for the object and image-spaces are numerically equal but of opposite sign. This remarkable property of lens-systems used in air was anticipated in the preceding section.

Oblique Planes.—One further deduction from the general theory of perfect lens-systems must be mentioned. The original treatment was limited to object- and image-planes at right angles to the optical axis. If we assume that the general object-plane O in fig. 4 is tilted to an angle ϵ with the optical axis, it is easily proved by a slight extension of the methods demonstrated in the proofs already given that such a tilted plane is also depicted as a tilted image-plane. From this it follows that *a perfect lens-system will give a flat image of any flat object, however the latter may be tilted with reference to the optical axis*, or even when the flat object lies parallel to the optical axis. The familiar use of the *swing-back or swing-front* of well-made cameras finds its full justification in this extension of the Gaussian theory. Moreover, as a straight line may be defined as the intersection of two planes, it follows that a straight line in any position whatever is also depicted as a perfectly sharp and straight line in the image-space. A telegraph-wire running in any direction through the field of view of a camera can therefore be sharply rendered from end to end by a proper use of swing-back or swing-front.

There is, however, an important reservation to be added: For normal planes we found that the image is perfectly similar to the object; this is not the case for objects in tilted planes. In their case the image displays the perspective which can be seen in any oblique view of a street-front, the nearer parts being shown on a larger scale than the more distant ones, and horizontal lines of the buildings all pointing towards one and the same " vanishing point ".

An important use can be made of this property of good lenses. It frequently happens that we find ourselves facing a tall building or a precipitous mountain-scene which subtends too large an angle to be covered with an ordinary camera when the plate is kept in the orthodox vertical position. If the subject is sufficiently tempting to

repay us for some considerable addition to the usual trouble of producing prints, we may tilt the camera regardless of the faulty perspective which must result, merely assuring that the subject is focused on the plate. By the enlarging process we can then rectify the perspective as is shown in fig. 7. For a perfect result a record should have been kept of the tilt of the plate and of the focal length of the lens employed. If we then set negative and enlarging paper at the recorded tilting angle with reference to each other, and employ an enlarging lens which gives a conjugate distance on the side of the negative equal to the focal length employed in taking the latter, a perfectly sharp image of correct perspective will be obtained. In

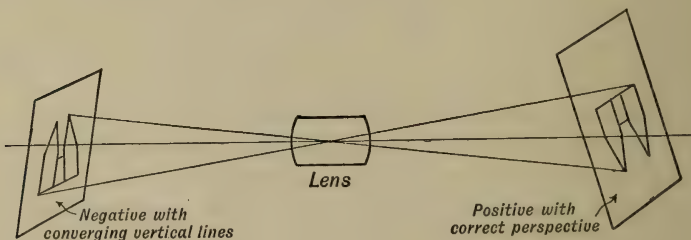


Fig. 7

practice it is not usually necessary to be very particular about the equality of the distances of the negative which have been specified; a satisfactory though possibly slightly untrue image will result if we adjust the relative tilt and the focus until the vertical lines of the negative become parallel on the enlarging screen.

When accurately carried out, the process will yield an image indistinguishable from one obtained from the same point of view by a wide-angle lens on a plate accurately adjusted to the conventional vertical position.

We are now ready to discuss a number of general properties of photographic lenses which are of great importance in the practice of photography, and we will begin with those properties which are inevitably present even in the most perfectly corrected systems.

Brightness of the Image, or Rapidity.—Lens-systems necessarily have a limited clear aperture, and in photographic lenses the aperture is very usually further restricted by a diaphragm. The latter is generally placed between the lenses so that it cannot be seen directly from either side of the lens-system. What we see is an image of the actual diaphragm or " iris of the system ", and these

images are known as the "entrance-pupil" in the case of the image seen from the side of the objects, and as the "exit-pupil" for the image-side. It is at once evident from fig. 8 that in the case of light from the usual distant objects the diameter of the admitted pencil of rays is determined by the entrance-pupil, and that if the actual iris were transferred from its normal position to one to the left of the front lens, it would admit a decidedly narrower pencil of rays. This renders it obvious that it would be absurd to determine the effective aperture by measuring the actual iris-opening; we must measure the diameter of the entrance-pupil, and this can easily be done by placing the eye at the principal posterior focal point F′, localizing the latter—if considered desirable—by a small hole in a

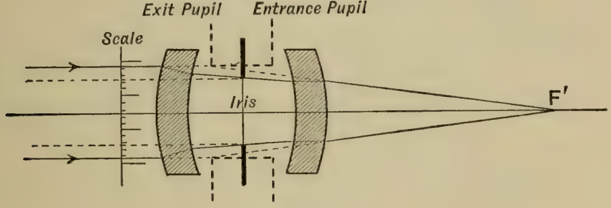


Fig. 8

piece of cardboard, and then reading the effective aperture off a scale placed close to the front lens. The effective aperture is practically always larger than the iris-opening, and may be 20 per cent and more in excess of it. An injustice is very commonly done to the makers of lenses by ignoring this simple fact.

By way of a slight digression we must note that the entrance-pupil has an important bearing on the theory of the perspective of the photographic image. If we imagine the iris closed to pin-hole size, the entrance-pupil will shrink to a corresponding small diameter, but will retain, at least very approximately, its distance from the first lens-surface. It follows at once that the centre of the entrance-pupil is the point of view which determines the perspective of the photographic image, and that the latter will be identical in its perspective with the image obtained by a pin-hole coincident with the centre of the entrance-pupil. This exact identification of the point of view can become important if photographs of comparatively near three-dimensional objects are to be accurately measured, as is done in photographic surveying.

The law which determines the brightness of the image is easily deduced by the following considerations:

Let O (fig. 9) be a small object sending light to the lens-system. Considered as a source of light, the object will obey the fundamental photometric law by illuminating the entrance-pupil at EP with an intensity inversely proportional to the square of the distance from O to EP. This distance may be considered as made up of the distance from the anterior focus F of the lens-system to O, which is the X_f of equation (8) and $= -f/M'$ if f is the anterior equivalent focal-length and M′ the magnification of the image produced by the lens-system, and of the distance from EP to F. As the entrance-pupil is never very far away from the first principal plane, we may call this second part of the distance $= f(1 + p)$, p standing for some small positive or negative fractional number. Combining the two

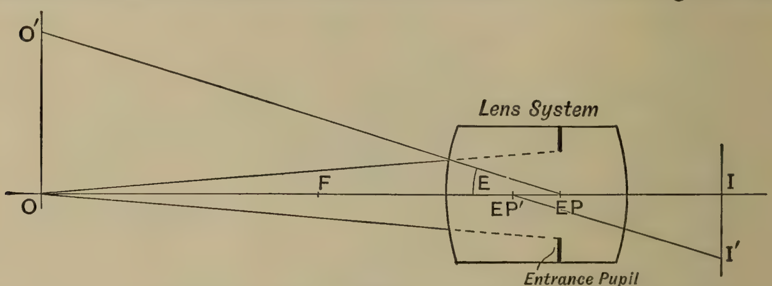


Fig. 9

parts of the total distance, we can say that the intensity of the light falling upon the entrance-pupil is inversely proportional to $f^2(1 + p - 1/M')^2$. The entrance-pupil will admit into and through the lens-system an amount of light of this intensity which is obviously proportional to the area of the pupil or to A^2, if we call the clear diameter of the pupil A. Hence the amount of light admitted is proportional to

$$A^2/f^2(1 + p - 1/M')^2.$$

This light will be concentrated by the lens-system in the image I of the object O. The linear size of this image will be proportional to the linear magnification M′, and the area of the image will be proportional to M'^2. The intensity or brilliancy of the image is therefore inversely proportional to M'^2, and, of course, also to the previously determined amount of light admitted by the entrance-pupil. Hence if k is a numerical constant which depends on the units of measurement employed, about which we need not here concern ourselves, we can turn our proportions into an equation

and claim that the brightness of the image, which we will call B, is given by

$$B = k\frac{A^2}{f^2(1 + p - 1/M')^2M'^2} = k\frac{A^2}{f^2[M'(1 + p) - 1]^2}.$$

For distant objects M′ becomes a very small fraction and may be neglected. We then obtain for distant objects:

$$B = k(A/f)^2,$$

which shows that the brightness of the image is proportional to the squared ratio of the clear aperture to the focal length.

In photographic practice we are more directly interested in the time of exposure required to obtain the desired density of the image. By a well-known though only approximately true law the time of exposure is inversely proportional to the intensity of the illumination which falls upon the plate, hence it will be proportional to the reciprocal of our first solution, and may be written

$$\text{Exposure} = t\left(\frac{f}{A}\right)^2[M'(1 + p) - 1]^2,$$

in which t stands for a constant which in practice is derived from an exposure-meter, a photometric device, or from experience, and which also varies with the inertia or speed-number of the plate employed. The ratio of focal length to aperture which now appears in the equation is usually called the f-number of the lens, and in British lenses is engraved on the iris-scale or on the Waterhouse-stops. The usual sequence of f-numbers, $f/4$, $f/5{\cdot}6$, $f/8$, $f/11{\cdot}3$, &c., was chosen because the squares of these numbers, to which the exposure is proportional, progress by successive doublings, and are thus convenient for mental calculations. The final factor in the equation only requires notice for near objects, and can nearly always be replaced by $(M + 1)^2$, if M is taken as the magnification-number with disregard of the negative sign required in the algebraical equations for an inverted image. It then leads to the simple rule that for near objects the f-number engraved on the diaphragm must be multiplied by $M + 1$ to determine the correct exposure. Thus if a plan is to be reduced to half-size, M will be $\frac{1}{2}$, and the stop engraved $f/8$ must be treated as having the f-number $8(1 + \frac{1}{2})$ or as $f/12$. If an enlargement to three times natural size were required, then the factor $(M + 1)$ would be 4, and the stop engraved $f/8$ would

have to be treated as $f/32$ in calculating the exposure. In some types of lenses the factor $(1 + p)$ which is attached to M′ in the complete formula may just about become sensible; in a landscape-lens with diaphragm in front of the lens p would be a negative fraction, whilst in a lens like the Busch "Bistelar" p would be positive. The former would require rather less, the latter rather more exposure on near objects than a normal photographic lens contemplated by the simple $(M + 1)$ formula.

The equations given above are strictly correct for objects near the optical axis, or near the centre of the field. If the object covers a field of considerable angular extent, then the images of its outer parts will be less bright than those of the central part, and the illumination of the plate may become unequal to an extremely serious extent if the angle of field is large. Referring again to fig. 9, and assuming for the present that the full aperture of the entrance-pupil remains effective for the oblique pencils, we see that an object O′, of the same intrinsic brightness as the central object O, but appearing at an angle E with the optical axis, will be farther from the entrance-pupil in proportion with secant E, and by the photometric law the illumination of the entrance-pupil would be smaller than that produced by O in proportion with $\cos^2 E$. But that is only part of the effect. As seen from O′ the diameter of the entrance-pupil in the plane of the diagram will be seen foreshortened in the ratio $\cos E$, and the area of the pupil will be correspondingly reduced. But the small object O′ is similarly foreshortened as seen from EP, and for that reason the factor $\cos E$ comes in yet again. The result is that the illumination at I′, the image of O′, will be less than that at I in proportion to $\cos^4 E$, and in order to produce the same exposure-effect the time of exposure will require to be increased in proportion to $\sec^4 E$. This factor grows very quickly in accordance with this little table:

$E =$	10°	20°	30°	35°	40°	45°
$\cos^4 E =$	0·94	0·78	0·56	0·45	0·344	0·25
$\sec^4 E =$	1·06	1·28	1·78	2·22	2·91	4·00

Even "narrow-angle" objectives reach $E = 20°$, for which the illumination in the margin is 22 per cent less than the central illumination. At $E = 30°$ the marginal illumination is only slightly in excess of half the central illumination, and at $E = 45°$ (wide-angle objectives) the marginal illumination sinks to one-fourth of the central illumination.

The inequality of illumination deduced from the photometric law is subject to modification by various disturbing causes. In the first place some of the light falling upon any glass-air surface is reflected back, and thus does not reach the image. This loss is always greater in the oblique pencils on account of the greater angles of incidence; it therefore tends slightly to aggravate the inequality of illumination. In the second place the constituent lenses of a system absorb some of the light, and particularly the photographically most active violet and ultraviolet light. Dense flint-glass and some of the modern dense barium-glasses are particularly bad in this respect. If one of the constituents is made of a highly absorbent glass, the absorption will affect the oblique pencils most

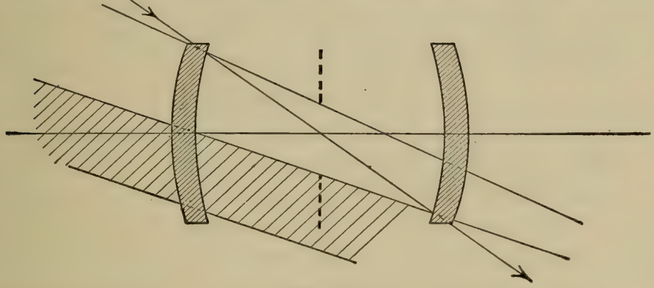


Fig. 10

if the lens is a concave one, because a concave lens is thickest towards its margin. In that case the inequality of illumination will be aggravated. On the other hand, a convex lens of highly absorbent glass will weaken the central pencils most, and therefore tends towards equalizing the illumination. Absorption can in this way modify the inequality of illumination to a very notable extent. It has frequently been suggested that a highly absorbent convex lens at a good distance from the entrance-pupil should be deliberately introduced for the purpose of equalizing the illumination, but as this cure is at the expense of rapidity it has not found favour. A third disturbing cause is known as the vignetting effect; it is the most serious one of the three, for it reduces the illumination to absolute zero for an angle E, which may be as low as 25° in the older rapid portrait and rectilinear lenses, and which rarely exceeds 45° or 50° even in the more compact modern lenses. The vignetting effect is due to the separation and the limited diameter of the front- and back components. Referring to fig. 10, it is easily seen that an oblique pencil filling the full aperture of the front-lens will fall

eccentrically upon the back lens, and a large part of the light will consequently be stopped from proceeding farther by the limited aperture of the back lens. At still greater obliquity, indicated by the heavily drawn ray with arrowheads, a limit will be reached at which only this single ray can get through. It will be obvious without elaborate proofs that the vignetting effect must increase the more rapidly the smaller the angle of obliquity of this limiting ray. Hence the angular diameter of the illuminated field has a very important bearing on the equality of illumination throughout the field, and a large diameter of the extreme illuminated field is of high value even though the plates to be used with the lens embrace only a comparatively small angle. At full aperture a lens with an illuminated field 90° in diameter (about an average figure in modern anastigmats) invariably gives less inequality of illumination than another with an illuminated field measuring only 75° or 60°. When the iris is closed down, the vignetting effect disappears for the central part of the field, but still becomes effective beyond a certain angle. This explains why the $f/11$ of a lens whose full aperture is $f/6$ gives more uniform illumination than the same aperture when it represents the full aperture of a slow lens. It also supplies the reason why true wide-angle objectives are always made with lenses the clear aperture of which measures several times the largest diaphragm-opening to be employed.

In the making of contact prints on bromide-paper a sovereign remedy for the inevitable inequality of illumination of all negatives is available; its unconscious application in the usual routine of "gaslight" printing explains the good results generally obtained by that process. If we expose the printing-frame at a suitably short distance from a fairly small source of light, the same photometric laws which account for the greater part of the unequal density of negatives are brought into action as an almost perfect compensating agent, for the thin marginal parts of the negative are illuminated obliquely and from a greater distance, and so receive less light. In the enlarging process the same compensating effect can be secured by making the illumination deliberately stronger for the centre of the negative. It will also be realized that a wise photographer should treat the full aperture of his lens as a last resource to be drawn upon only in desperate cases. The vignetting effect will thus be avoided or diminished in the great majority of negatives.

Depth of Focus.—It was shown in the general theory of perfect lens-systems that a definite object-plane corresponds to any

chosen position of the image-plane or sensitive plate. Consequently a geometrically sharp image can only be expected if all the objects lie in one plane, and are therefore in the nature of a flat plan or drawing. In all other cases most of the objects included in the three-dimensional view will be more or less out of focus, and therefore cannot be expected to be depicted with perfect sharpness. A skilled photographer can minimize this difficulty to a surprising extent by proper use of the swing-movements of the focusing screen or of the lens, and by a proper choice of the exact point of view, for by these means the sharply rendered object-plane can be made to run through the scene at such distances and tilts that all the principal objects lie close to it and are therefore sharply depicted. Specialists in the production of specimen photographs for advertizing purposes are frequently amazingly clever in taking advantage of

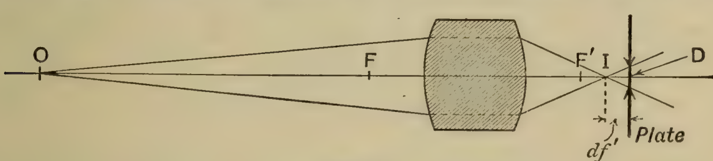


Fig. 11

these possibilities, and in thus supplying remarkably sharp pictures really taken with full or large aperture, even with lenses afflicted with considerable curvature of field. But when the view is given instead of being cunningly selected, the limits of skilful focusing are more restricted, and then the clear aperture of the lens must be reduced in order to obtain the desired sharpness of all the details.

If the lens-system indicated in fig. 11 depicts an object O sharply at I, then the rays from O which the system allows to pass will fill a double cone with apex at I. A sensitive plate placed at distance df' from I will cut this cone of rays in a circle of a finite diameter D, which is obviously proportional to df' and also to the angle of the cone of rays. The plate will therefore render the object-point O as a circular patch instead of a point, and the image will become diffused or indistinct. But as there is a fairly definite limit to our acuity of vision, the diffusion will not be unpleasantly noticeable up to a certain value of D. The distance df' at which this critical value of D is reached defines the "depth of focus" of the lens-system. For photographs which are to be viewed by the naked eye, D is usually assigned the limiting value 0·01 in. or 0·25 mm., which may be considered tolerable for landscapes of at least whole-plate size. Small

pictures and especially negatives intended for enlargement call for a decidedly lower value, and 0·004 in. or 0·1 mm. will be found a more appropriate estimate. Even this would be inadmissible if the image is to give the impression of absolute sharpness, like that of an engraving, and 0·001 in. may then have to be adopted as the limit. The last figure comes fairly close to the distance between the silver-grains in fast dry plates, so that it will rarely be necessary to demand a still smaller diffusion of the image. The depth of focus df' which corresponds to any adopted value of D depends upon the angle or rate of convergence of the cone of rays. For fairly distant objects this is sensibly the ratio of clear aperture to focal length, and gives the relation

$$df' = D \times f\text{-number.} \quad \ldots\ldots\ldots\ldots\ldots (12)$$

For near objects depicted at a magnification (treated as positive) = M, we showed that the usual engraved f-number requires multiplying by (M + 1), hence in this case

$$df' = D(M + 1)f\text{-number.} \quad \ldots\ldots\ldots\ldots (12^*)$$

A small table for the case of distant objects will display the values which result for df':

Limiting Value of D.	0·01 in.	0·004 in.	0·001 in.
df' at $f/4$	0·04 in.	0·016 in.	0·004 in.
df' at $f/8$	0·08 ,,	0·032 ,,	0·008 ,,
df' at $f/16$	0·16 ,,	0·064 ,,	0·016 ,,
df' at $f/32$	0·32 ,,	0·128 ,,	0·032 ,,

For practical purposes the most important conclusion is that the depth of focus is proportional to the f-number, and can be raised to any required amount by making the diaphragm-opening small enough. If there is no objection to the loss of brightness of the image, this method is therefore always available, and is in fact employed habitually by every practical photographer. There is, however, a limit below which the geometrical law on which our equations are based is invalidated by optical interference effects or " diffraction ". By reason of the finite wave-length of light, no optical instrument can render an object-point as a true point-image; the image is always a tiny patch of light surrounded by delicate diffraction-rings of very low intensity, and the diameter of the " spurious disc "

is proportional to the f-number or inversely proportional to the clear aperture of the lens-system. The light-distribution can be calculated by rather difficult integrations, but the generally adopted values are really based on direct measurements. In terms of the f-number, the diameter of the sensibly bright part of the spurious disc in inches may be taken as

$$\text{Diameter of spurious disc} = 0{\cdot}00002 \text{ in.} \times f\text{-number},$$

and comes out so small as to be photographically uninteresting for the usually employed f-numbers.

For the three standard values of the permissible diffusion D which we have adopted we obtain, by transposition of the last equation,

$$\text{Largest permissible } f\text{-number} = \text{D}/0{\cdot}00002 \text{ in.},$$

which gives

$$\begin{aligned} &\text{for D} = 0{\cdot}01 \text{ in.: } f\text{-number} = 500, \\ &\text{for D} = 0{\cdot}004 \text{ in.: } f\text{-number} = 200, \\ &\text{for D} = 0{\cdot}001 \text{ in.: } f\text{-number} = 50, \end{aligned}$$

and shows that diffraction can only become sensible when the highest degree of sharpness of definition is aimed at. In the taking of photomicrographs with the compound microscope, the f-number on the side of the photographic plate is rarely *less* than 200!

In the application of the camera to landscapes and to naked eye objects generally another aspect of the limit imposed by diffraction is more useful. According to astronomical experience, the smallest angular subtense at which a lens of clear aperture = A in. can still separate two points or lines is given by

$$\text{Limit of angular resolution} = 4{\cdot}6 \text{ sec. of arc}/\text{A in.}$$

In the photography of natural objects we may generally be well satisfied if the photograph shows every detail which the naked eye could distinguish from the same point of view. Now the limit of resolving power of the human eye is just about 60 sec. of arc, and putting 60 on the left of the last equation and transposing for A we find

$$\text{Least permissible clear aperture} = 4{\cdot}6/60 = 0{\cdot}077 \text{ in.}$$

Very few iris-diaphragms can be closed to less than this small diameter, and we see again that diffraction will rarely affect the sharpness of ordinary photographic images.

We may therefore adhere to the simple geometrical treatment of the depth of focus problem, and will complete its solution by deducing the range of distance in the object-space which can be covered in any given case. This solution is easily obtained from equations (8), the third of which on introducing $f = -f'$ by (11*) gives

$$X_f X'_f = -f'^2,$$

X_f being the distance of the object from the anterior focus, and X'_f the distance of the image from the posterior focus. Differentiation of the equation gives

$$dX_f = dX'_f f'^2/X'^2_f,$$

and introducing by the first of (8) $X'_f = -f'M'$ we obtain

$$dX_f = dX'_f/M'^2.$$

dX'_f, the small shift of the image-plane, may obviously be replaced by our df' of equation (12*), and we thus arrive at the general solution

$$dX_f = f\text{-number} \times D(M + 1)/M^2 \quad \ldots\ldots\ldots (13)$$

by again using the simple positive magnification-number. dX_f represents the *range* of object-distance from the sharply focused object to one at which the diffusion-tolerance D is reached. As this range can be applied to either side of the sharply focused object, the most useful solution takes the form

$$\text{Object-range} = f\text{-number} \times 2D(M + 1)/M^2 \ldots\ldots (13^*)$$

As an example, portraits are usually about one-tenth of natural size; therefore $M = 0{\cdot}1$. If we allow $D = 0{\cdot}004$ and intend to work at $f/8$, we find

$$\text{Object-range} = 8 \times 0{\cdot}008\ (1{\cdot}1)/(0{\cdot}1)^2 = 7{\cdot}2 \text{ in.}$$

This range will be further diminished if a larger scale of the image is required, or if a larger aperture is used, and it becomes evident that a movement of very few inches may spoil the focus of a portrait.

The object-range becomes painfully small at considerable actual magnification. For a 6-times enlargement with the stop marked $f/8$, and allowing $D = 0{\cdot}01$ in., we find

$$\text{Object-range} = 8 \times 0{\cdot}02 \times 7/36 = 0{\cdot}031 \text{ in.},$$

or only one thirty-second of an inch. A slight buckling of a paper-original may therefore render a sharp focus impossible.

For high microscopical magnifications the object-range goes down to a few one-hundred-thousandths of an inch, although the pencils of rays which arrive at the plate have only a convergence corresponding to $f/500$ or thereabouts!

On the other hand, the object-range becomes very large for distant views, and the solution (13*) then becomes both inconvenient and inaccurate. For landscape purposes it is therefore preferable to calculate a sequence of object-distances corresponding to successive lengthening of the camera-extension in steps of the order of the average depth of focus. This leads immediately to the best method of constructing a focusing scale for hand-cameras, and that will be the chief application of this method.

The slightly modified third equation of (8) already used gives

$$X_f = - f'^2/df',$$

df' standing for the camera-extension beyond the infinity-focus, and X_f for the distance of the sharply focused object from the anterior focus. The photographer will probably estimate or measure the distances from his own position, and a small correction has to be applied to allow for the additional distance from the anterior focus to the stand-point of the photographer, which will usually be about $2f'$. For hand-cameras one-tenth of an inch will be a suitable interval for the focusing scale. Ignoring the negative sign which analytical geometry would assign to X_f and its correction, the calculation becomes extremely simple. Taking as an example a lens of 6-in. focal length and estimating the correction of X_f at 12 in., we have

$$\text{Object-distance} = X_f + 12 \text{ in.} = 6^2/df' + 12 \text{ in.},$$

and can calculate mentally or by slide-rule:

for df' =	0	0·1 in.	0·2 in.	0·3 in.	0·4 in.	0·5 in.
$6^2/df'$ =	∞	360 in.	180 in.	120 in.	90 in.	72 in.

or on adding 12 in. and turning the result into yards:

Object-distance in yards:	∞	$10\frac{1}{3}$	$5\frac{1}{3}$	$3\frac{2}{3}$	$2\frac{5}{6}$	$2\frac{1}{3}$

which it would be safe to engrave as

∞	10	5	4	3	$2\frac{1}{2}$

An extremely neat device was described in a photographic journal a number of years ago for embodying the actual depth of focus in the index of such a focusing scale. It consists in marking, instead of the single line which would indicate the exactly focused distance (dotted in fig. 12), a series of U-shaped double indices with lines at distances to either side of the true index-line equal to the calculated depth of focus for various *f*-numbers. Thus the table of df' gives for the usual tolerance D = 0·01 in. a depth of focus of 0·04 in. at *f*/4, 0·08 in. at *f*/8, and so on. The forked index for *f*/4 therefore has arms 0·08 in. apart, the *f*/8 index has them 0·16 in. apart, &c. We can then see at once that, at the focal adjustment shown in fig. 12, objects distant from 7 yd. to 4·6 yd. would be sufficiently sharp at *f*/4, whilst at *f*/16 objects from 20 yd. (remember the reciprocal nature of the scale!) down to 3·4 yd. would be in respectable focus. Conversely the arrangement will indicate automatically what stop must be used in order to cover a certain range of distance.

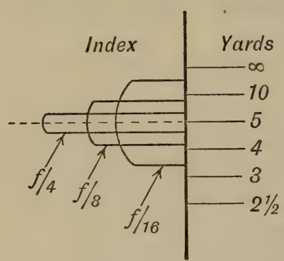


Fig. 12

The fact expressed by (8), that the distance X_f corresponding to a certain value of df' is proportional to the square of the focal length f', is the chief justification of the use of short focal lengths in hand-cameras. The *real* advantage is, however, inversely proportional to the focal length itself and not to its square, for, on account of the smaller scale of the image obtained with a short focal length, the tolerance D must be proportional to the focal length in order to secure the same amount of delicate detail.

False Light and Ghost-images.—Although perfectly corrected as regards sharpness and correct perspective of the image, a photographic lens may be almost useless for certain purposes on account of scattered light or more or less sharply focused secondary or " ghost " images being superposed upon the principal image, and falsifying its contrasts of light and shade or adding spurious and misplaced detail.

Imperfect blacking of the edges of the constituent lenses and of metal-parts of the mount frequently causes serious amounts of diffusely reflected light to be thrown upon the plate and greatly to diminish the brilliancy of the image, especially at and near full aperture. To minimize this source of false light, an efficient dead-black pigment should be rubbed (light painting is insufficient) into

the ground edges of lenses before mounting, and as it is extremely difficult to produce a real dead-black on metal-surfaces, as little illuminated metal as is possible should be visible on looking at the lens from the side of the focusing screen. Where it can be applied, black velvet is by far the most efficient covering medium for exposed metal-surfaces.

The most serious source of false light is, however, represented by reflection at the external surfaces of the components of a photographic lens. When light falls upon a polished surface which separates glass from air or vice versa, then from $4\frac{1}{2}$ to 6 per cent of the incident light is reflected back at the surface, whilst the rest is refracted and proceeds in the intended direction towards the sensitive plate. In fig. 13 two separated lenses are shown and the heavily-drawn ray represents the useful light. On meeting the first surface, about 5 per cent of the light is reflected back into the landscape, and is merely lost. At the second surface 5 per cent of the light reaching it is again sent back by reflection, but unfortunately not all of this is definitely lost, for on its return journey it meets the first surface, which reflects 5 per cent of the 5 per cent or $\frac{1}{4}$ per cent of the useful light back in the direction towards the sensitive plate, and so provides a first instalment of false light, marked (1) in the diagram. In a corresponding way the light reflected at the third glass-air surface is partly reflected towards the sensitive plate at the second and first surfaces, and contributes instalments (2) and (3) of false light. Evidently this production of false reflection grows like an avalanche as the useful light reaches further glass-air surfaces, and it is easily seen that if there are n separated components, the total number of glass-air surfaces will be $2n$, and the total number of double reflections will be

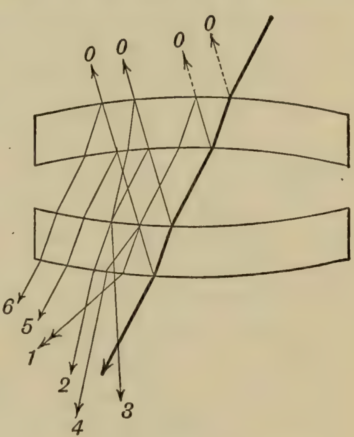


Fig. 13

$$(2n - 1) + (2n - 2) + \&c. + 1 = n(2n - 1).$$

This gives for

Number of components:	1	2	3	4
Number of double reflections:	1	6	15	28

Cemented surfaces produce only extremely feeble reflection, and need not be taken into account.

As each of the double reflections represents about $\frac{1}{4}$ per cent of the incident light from which it is derived, it will be seen that whilst for a single cemented lens (photographic landscape-lenses!) the false light is practically insignificant, it amounts to $1\frac{1}{2}$ per cent of the average intensity of the incident light for a doublet, to 4 per cent for a triplet, and to 7 per cent for a system of four components separated by air.

Each of these false reflections produces an image of all objects in front of the lens, but the vast majority of these images are formed close to or within the lens, and are therefore utterly out of focus on the sensitive plate. The effect on the latter is therefore largely one of uniformly scattered light, which lights up the shadows and causes a more or less dense deposit of silver in parts of the image which ought to be nearly clear glass. This causes the false light to be frequently misinterpreted as over-exposure, but the thinness of the high lights and the absence of detail in the shadows tell a different story.

The effect of doubly reflected light is usually diminished at reduced aperture because some of the tracks of the undesirable rays are then cut through by the diaphragm. On the other hand, an aggravation is apt to occur when there are many of these double reflections present, for one or more of them are then likely to have a comparatively long focus and to produce a more or less sharp " ghost "-image of bright objects on the sensitive plate. Thus in a church-interior a well-exposed image of some dazzling window, the true image of which may be badly halated or even solarized, may appear on the floor or upon a solid wall.

A special case of a double reflection was frequently troublesome with the ordinary landscape lenses of fifty years ago, but may still turn up in special cases. It is known as a " flare-spot " or diaphragm-spot. As was pointed out earlier, any optical system depicts everything confronting it or even within it, and it does this not only by the exclusive refraction effect but also by combined reflection and refraction effects. The flare-spot is an image of the diaphragm produced by this combined effect in the lens or lenses between the diaphragm and the sensitive plate, as is shown in fig. 14. This image may find its focus close to the sensitive plate, and as it is formed by the full aperture of the lens, it may become comparable in brightness with the true landscape-image when the diaphragm-opening is small,

and a dark and more or less sharply defined circle will then appear in the centre of the negative, which prints as a flare of light in the positive, whence the name. It can be rendered harmless by a fairly considerable change in the distance from diaphragm to lens, but only at the expense of loss of definition and aggravated curvature of field. Avoidance of small diaphragm-openings is therefore sometimes to be preferred.

All the sources of false light which have been mentioned may be beneficially affected by arranging a generously dimensioned ray-shade

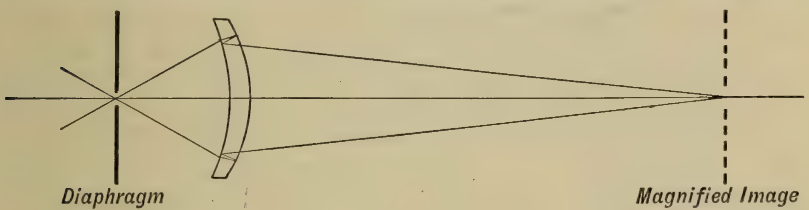


Fig. 14

in front of the lens in the form of an internally black box or tube, with an opening only just large enough to admit all the light which contributes to the regular image. With telephoto-lenses such a hood is almost a necessity.

The Aberrations of Photographic Objectives

Modern anastigmatic lenses with a rapidity not exceeding $f/6$ approach so nearly to the properties of a perfect lens-system that the residual defects may be treated as negligible in all ordinary photographic work, and that the results to be expected may be predicted with sufficient precision by the criteria already given in preceding sections.

In the older types of landscape, rectilinear, and portrait lenses, in ultra-rapid anastigmats and in lenses required for the photographic reproduction of maps or drawings with almost microscopical sharpness and with freedom from distortion, the approach to theoretical perfection is frequently insufficient, and it then becomes desirable to know the nature and relative importance of the residual defects, and to be able to recognize them individually and to estimate their magnitude.

The aberrations of lens-systems are conveniently divided into two classes, firstly, those which are present even when light of only

one definite colour or wave-length is employed; secondly, those additional aberrations which become manifest when objects are employed which send out light covering a more or less extended range of colours and wave-lengths. Aberrations of the first class are described as *spherical aberrations*, those of the second class as *chromatic aberrations*, or in certain cases as the *chromatic variation* of particular spherical aberrations. On account of this last type of aberrations it will be convenient to begin with the consideration of the spherical aberrations which are present in monochromatic images.

Not a single one of the numerous classes of aberrations can be completely corrected in actual lens-systems of the usual aperture and diameter of field. Either calculation or a sufficiently searching direct observational test will always reveal residuals. This requires emphasizing, because the usual descriptions in books are based on a first approximation theory according to which complete correction is possible, and because, under the stress of competition, the catalogues of makers of lenses are also usually silent on the subject of residual or " zonal " aberrations. The result is that when the owner of a lens finds these residuals, either by personal trials or by submitting it to official test, and obtaining an imposing and depressing list of measured aberrations—usually without any statement as to how these compare with the amounts to be expected in the particular type—then severe dissatisfaction is created, and the impression is gained, and probably acted upon, that a highly imperfect instrument has been palmed off upon a trustful customer. A little more candour on the part of the makers, and much more practical experience and knowledge on the part of the framers of official reports, appear highly desirable.

We will now discuss the various classes of spherical aberration.

1. **Axial Spherical Aberration.**—When a simple convex lens receives light from an object-point on its optical axis, only the rays which pass close to the axis are brought to a common focus. Rays through the outer parts or " zones " of the lens come to a shorter focus and a confusion of rays results. Referring to fig. 15*a*, rays close to the axis might have a focus at F_0, and the extreme marginal rays might cut the axis at F_1. F_1F_0 would then be called the longitudinal spherical aberration of the lens. In first approximation this aberration grows with the square of the aperture, and the rays from the half-aperture may therefore be expected to come to focus at $F_{\frac{1}{2}}$, so that $F_{\frac{1}{2}}F_0 = \frac{1}{4}F_1F_0$. On the basis of the stated approximate law of change with the square of the aperture, it is easily shown that

the greatest constriction of the confused bundle of rays lies where the extreme marginal rays diverging from their focus F_1 cut through the rays from the half-aperture converging towards $F_{\frac{1}{2}}$, and that this "disc of least confusion", which obviously represents the photographically interesting measure of the defect, grows with the

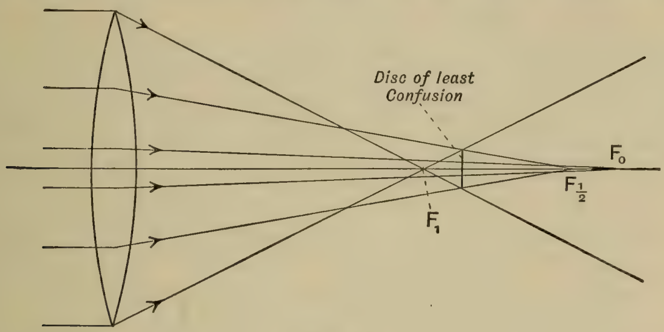


Fig. 15*a*

cube of the aperture. It therefore is reduced to one-eighth of its full aperture value when the lens is stopped down to half-aperture, and this extremely rapid diminution is the reason why excellent sharp photographs can be taken with ordinary landscape and wide-angle objectives, in which the spherical aberration cannot be cor-

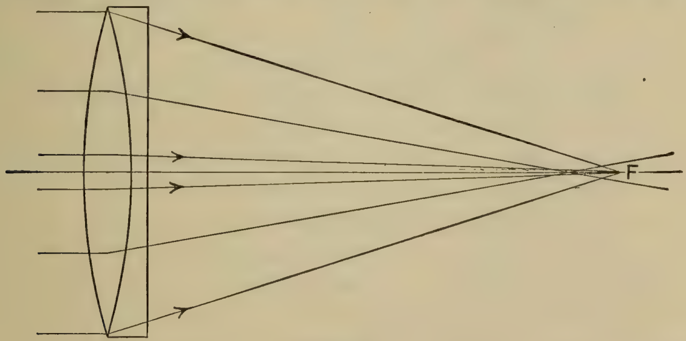


Fig. 15*b*

rected without going from the frying-pan of slightly unsharp axial images into the fire of terrific extra-axial aberrations.

As the location of the sharpest image shifts with every change of aperture, such lens-systems shouid be focused with the aperture at which the exposure is to be made, which is in fact advisable with any lens when the light is sufficient.

In compound lenses the spherical aberration can be corrected so as to bring the paraxial and the extreme marginal rays to a common focus F (fig. 15*b*), and if only " primary " aberration following the square of the aperture law were present, a system so corrected would be perfectly free from spherical aberration. In reality there is always present in very sensible magnitude a " secondary " longitudinal spherical aberration which grows with the fourth power of the aperture. The best possible compromise is then still attained by establishing the common focus of paraxial and extreme marginal rays; but as the primary and the secondary aberration follow different laws they will not cancel each other perfectly at intermediate apertures, and there results a zonal spherical aberration which reaches its longitudinal maximum for 0·7071 of the full aperture, invariably in the sense of " undercorrection ", that is, the intermediate zones have a shorter focus than the paraxial and marginal rays. A disc of least confusion again results, and it is the size of this disc which sets the limit to the maximum permissible aperture of " spherically corrected " rapid lenses.

The seriousness of a given residual of spherical aberration is most directly determined by measuring the diameter of the brightest obtainable image of a point of light and comparing this with the allowable diffusion, which will usually be about 0·004 in. for ordinary photography. With the small amounts of aberration permissible in good lenses, the measured diameter of the unsharp image is always much smaller than the geometrically calculated disc of least confusion; moreover, the visually brightest and sharpest image does not coincide in its location with the geometrical disc of confusion. These disagreements, which hold equally for other aberrations, are due to the now well-established fact that in the presence of moderate amounts of aberration the interference of the actual undulatory light produces results at and near the focus profoundly different from those predicted by the purely geometrical ray-theory.

For extra-axial image-points the aberrations are of a far more complicated type. Joseph Petzval, the designer of the famous portrait-lens, was undoubtedly in possession of a complete analysis of these aberrations in both first and second approximation as early as 1840, but he never published either his proofs or even the complete explicit formulæ. An elegant and perfectly rigorous discussion of the primary aberrations of oblique pencils was, however, given by the Munich astronomer Seidel in 1856, who proved conclusively that the pencils of rays of moderate aperture which pass at moderate

angles through any centred optical system are subject to *five* and *only five* different primary aberrations, namely:

1. Uniform *spherical aberration*, equal to that of the axial pencil, for pencils at every obliquity.
2. An unsymmetrical deformation of extra-axial image-points known as *coma*.
3. A symmetrical disarrangement of the rays of an oblique pencil, chiefly characterized by the formation of two linear images or "focal lines" at different distances from the lens and at right angles to each other, with elliptical discs of confusion between and beyond the focal lines instead of a single sharp point-image. This aberration is called *astigmatism*.
4. *Curvature of the field*.
5. *Distortion*.

Numerous treatments of the aberration problem have been published since Seidel's time, and some of these go further by including the effect of non-spherical or "figured" refracting surfaces, and by giving a more or less complete account of the secondary aberrations of oblique pencils.

In order to simplify the discussion we will assume that the test-object consists of a long horizontal straight line crossed at regular intervals by shorter vertical lines. White lines on a dark background are greatly to be preferred to black lines on a white ground, and white cotton threads stretched over a suitable flat frame are perhaps the simplest and yet efficient realization of our test-object. We shall assume that the optical axis of the lens under test is directed at right angles towards the central crossing point of the lines, and that the image is examined on a fine-grained focusing screen. In the case of symmetrical objectives the distance of the test-object has no very important effect, as the aberrations of such objectives are comparatively insensitive to change of distance.

For unsymmetrical objectives, especially those of rather long build, the distance of the test-object must be reasonably close to that for which the objective is intended to be used, for unsymmetrical objectives are apt to give very unsatisfactory images if the intended distance of the object is widely departed from.

We will now describe the four primary aberrations which occur only in the extra-axial image-points.

2. **Coma.**—In the presence of pure coma the smallest obtainable geometrical image of an extra-axial object-point assumes the

characteristic shape shown in fig. 16, consisting of a circle extended by two tangents which intersect under an angle of 60° and form the point or head of the complete coma-patch, as it is usually called. The axis of symmetry of the figure passes through the optical axis of the lens-system, and the coma is called inward if the point C is directed towards the axis, outward if C points away from the axis. The central rays of the oblique pencil aim at C, the extreme marginal rays are uniformly distributed around the circumference of the complete circle from which the figure is derived, and the rays from intermediate zones of the aperture pass through the rest of the enclosed space. There is a very pronounced concentration of light near the point of the figure, and very weak light near its opposite round end. The linear dimensions of the figure grow with the square of the aperture and in strict proportion with the distance of the image-point from the optical axis. The coma therefore diminishes rapidly when the clear aperture is reduced, and this is the only means of controlling it in a given lens-system. On our test-object it will cause a symmetrical diffusion of the horizontal line, growing in seriousness as the distance from the axis increases,

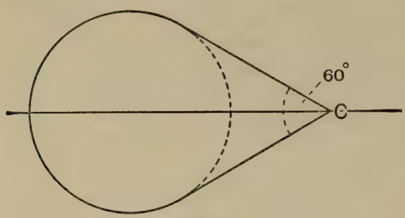


Fig. 16

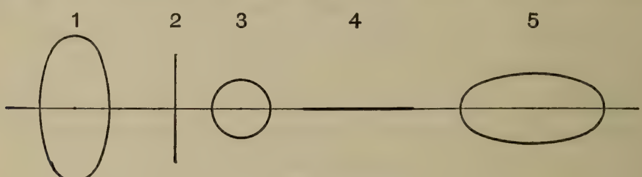


Fig. 17

and an unsymmetrical diffusion of the vertical lines which, when focused as sharply as is possible, will show a bright hard edge on the side of the head of the coma-patch and feeble diffused light on the other edge. The seriousness of the defect may be estimated by measuring the spurious width of the vertical lines.

3. **Astigmation.**—In the presence of pure astigmatism the image of an extra-axial object-point on the horizontal centre-line of the focusing screen undergoes highly characteristic changes when the camera is racked in and out. At a certain adjustment a

vertical ellipse with axes as 3 to 1 will be found (fig. 17, 1). A small change of camera-extension will cause the image to assume the form of a vertical line (2). A further change by an equal amount will produce a circular disc (3) of a diameter equal to half the length of the focal line (2). Yet another equal change of focal adjustment will produce a horizontal focal line (4) equal in length to (2), and a final change will yield a horizontal ellipse (5) equal in size and shape to (1). Outside this range the diffused image steadily grows in size and approaches to circular outline. If the vertical deformation of the image is found nearest the lens (or with least camera-extension), the astigmatism is called undercorrected or positive; it is called over-corrected or negative if the horizontal deformation is found nearest the lens. It is easily seen that the horizontal line of our test-object will be perfectly sharp if the focal adjustment corresponds to (4), and the vertical lines will be sharp when the adjustment is that for (2). At adjustment (3) both lines will be equally diffused, and at all other adjustments of the focus their diffusion will be unequal.

The difference in focus of the two focal lines at any particular distance from the centre of the focusing screen is independent of the aperture, but the length of the lines grows directly as the aperture. The resulting *diffusion* can therefore be diminished by cutting down the aperture; but whilst a reduction of the aperture to one-half diminishes the spherical aberration-disc to one-eight and the coma-patch to one-quarter, it only halves the astigmatic diffusion, and it becomes apparent why astigmatism has always been the chief enemy of good definition at large apertures. When image-points at different distances from the axial image are considered, it is found that the astigmatic difference of focus and the diffusion of the image resulting from it at any given aperture grow with the square of the distance from the centre of the plate. It follows that a lens suffering chiefly from astigmatism, which gives tolerable definition on a quarter-plate at $f/8$, would have to be cut down to $f/32$ to give similar definition on a whole-plate. This explains the minute aperture to which wide-angle lenses had to be cut down in pre-anastigmat days.

4. **Curvature of the Field.**—The difference of focal adjustment for horizontal and vertical lines due to astigmatism, and its increase with the square of the distance from the centre of the field, implies curvature of the latter, for even supposing that the horizontal line were sharply in focus across the whole field, the vertical lines would be out of focus, and, on account of the square of the distance law, could only be focused simultaneously on a curved focusing screen.

As a rule, both the horizontal line and the set of vertical lines are in focus on two curved surfaces which touch each other in the optical axis, and become more and more separated towards the margin of the field of view.

Seidel's fourth aberration establishes exact and simple relations between these curvatures of the field. Taken by itself, the fourth term states that if any centred lens-system is free from astigmatism, then the sharpest image of any flat object will lie on a surface of the curvature determined by the famous Petzval sum:

$$\frac{1}{R'} = -\Sigma[(N' - N)/NN'r].$$

This sum is to be worked out for all the refracting surfaces of the system, N being the refractive index of the medium to the left, N′ that to the right of each surface, and r being the radius of curvature of each surface, positive if the centre lies to the right of the surface. The R′ thus calculated gives the radius of curvature of the field of the anastigmatic lens-system, subject to the sign-convention stated for r, and, of course, in the same unit of length as that employed for the radii of curvature of the refracting surfaces. The remarkable property of the Petzval-curvature is that it depends only on refractive indices and radii, but is entirely independent of the thickness or separation of the constituent lenses of the system, and also independent of the conjugate distances of object and image. In practically all the older photographic lenses the value of R′ was from minus one to minus one and a half times the equivalent focal length, and the field, if free from astigmatism, was thus strongly rounded towards the observer of the focusing screen, and could not be simultaneously focused on a flat plate. In the modern anastigmats, as far as they really deserve that name, the value of R′ is from minus four to minus twenty times the equivalent focal length, or at least three times that of the old lenses. It will be rendered clear presently—in the section on secondary aberrations—why a large negative value of R′ is retained, instead of making R′ infinite. When the astigmatism is not corrected, then the third and fourth Seidel terms taken together establish another highly important and valuable relation. The astigmatic diffusion-image on the Petzval surface always has the form of the horizontal ellipse (fig. 17, 5), the two focal lines lie on the same side of the Petzval surface, and the distance of the vertical focal line from the Petzval surface is exactly three times the distance of the horizontal focal line. It is easily seen that if the astigmatism were of the

undercorrected type the curvature of the two astigmatic image-surfaces would be even worse than the Petzval curvature, and would render a lens of the older types so corrected almost useless. The invariable practice was therefore to establish a suitable amount of overcorrected astigmatism which would throw the astigmatic image-surfaces beyond the rounded side of the Petzval surface, and would thus flatten the field. The most favoured correction was such that the vertical lines would have a flat field and the horizontal line a curvature of field equal to two-thirds of the Petzval curvature. But sometimes, especially in wide-angle objectives, the field was rendered flat for the circular images (fig. 17, 3); in that case the horizontal line would have a roundness of field and the vertical lines a hollow field each of half the Petzval curvature.

5. **Distortion.**—This defect was dealt with in the section on correct perspective, and we need only add that the dislocation of an image-point from the position where it would be if the perspective were correct grows with the cube of the distance from the centre of the field, and thus becomes manifest chiefly in the extreme marginal parts of the plate. Frequently it is convenient to express the distortion as the percentage which the dislocation of the image bears to the distance of the latter from the centre of the field. This percentage-distortion grows with the square of the distance from the centre of the field. In lenses for the reproduction of maps, less than 0·1 per cent of distortion in the marginal part may be objectionable. In landscapes and portraits several per cent of distortion would hardly be noticed.

It may finally be added that all the statements in this section referring to the "horizontal" and "vertical" lines of the test-object and to the horizontal and vertical focal lines of astigmatism become applicable to any part of the field of view if, with reference to the centre of the field, horizontal is replaced by "radial" and vertical by "circumferential" or "tangential".

Secondary Oblique Aberrations

The five Seidel aberrations can be accurately expressed and calculated by comparatively simple algebraical formulæ, and there would be no difficulty at the present time in designing lens-systems completely corrected with reference to all five primary aberrations. Such a system would be almost ideally perfect if restricted to a comparatively small aperture and to a field of perhaps 15° or even up to 30° in angular diameter. At a larger aperture and field

the totally neglected secondary aberrations would come in with their full amount, and would lead to extremely rapid deterioration of the image beyond the limits of aperture and field within which these secondary aberrations are small. There are nine of these secondary aberrations, and although most of them cannot be removed, they can be compensated to some extent by playing out opposite residuals of primary aberration against them, and in this way a skilful designer can reduce the visible effect of the higher aberrations to something like one-quarter of their uncompensated magnitude. Moreover, the calculations aiming at this result will disclose any particularly large type of secondary aberration, and will lead to modifications of the design which tend to diminish the particular type.

It was described in the paragraphs on axial spherical aberration how this compensating trick is worked in that case. We will now briefly review the remaining eight secondary aberrations.

2*a*. **Secondary Coma.**—There are three different types of secondary coma. The first type gives a diffusion-patch very similar to that shown in fig. 16, but with the tangents at the point meeting at an angle of 83·6°; its size grows with the fourth power of the aperture and directly as the distance from the centre of the field. By playing out primary coma against it, its effect at full aperture can be reduced to less than one-quarter throughout the field, and it is then usually harmless. The second type by itself yields a coma-patch of precisely the form of fig. 16, and follows the same aperture law as the primary coma, but its growth in the field is proportional to the cube of the distance from the optical axis. It can be completely compensated for all diaphragm openings, but only for one particular distance from the centre of the field. There is then left a zonal variation of the coma in the more central parts of the field and a rapid rise of coma in the remoter parts of the field. The latter phenomenon accounts for the extremely sudden falling off in definition beyond a certain field which is characteristic of certain lenses when tried at full aperture. The third type of secondary coma yields a *linear* diffusion of the image with a strong concentration of light at that end of the line which forms the focus of the central rays. Its law of change is identical with that of the second type, but the compensation by primary coma is less perfect. The third type does not seem to reach such large amounts as the second.

3*a*. **Secondary Astigmatism.**—There is only one form of *pure* secondary astigmatism. It produces the same sequence of cross-sections as the primary astigmatism, from which it differs

only in so far as the primary astigmatism grows with the square of the distance from the centre of the field, whilst the secondary astigmatism grows with the fourth power of that distance and thus increases at a formidable rate beyond the point at which it first becomes sensible. By playing out primary astigmatism of opposite sign against it, the secondary form can be completely neutralized at some particular distance from the centre of the field, and there will then be a zonal variation of the astigmatism of the sign of the primary astigmatism in the more central parts of the field, and a rapidly increasing excess of secondary astigmatism beyond the corrected zone. In good anastigmats the latter is therefore laid fairly close to the margin of the normal field of view.

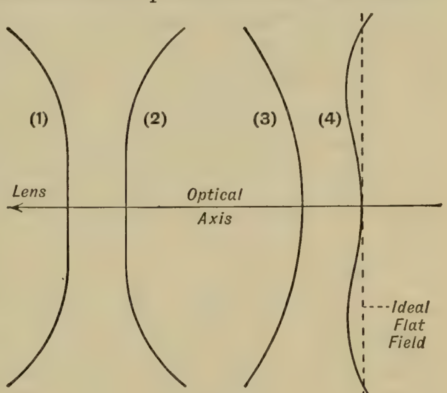


Fig. 18

4*a*. **Secondary Curvature of the Field.**—The secondary departure from a flat field grows with the fourth power of the distance from the optical axis, and thus affects sensibly only the more remote parts of the field. In the absence of Petzval curvature the field would therefore assume a saucer-shape (fig. 18, 1 or 2). In all existing types of anastigmatic lenses the secondary curvature of field is that of (2) or "hollow", and it will be at once clear that, accepting this statement, the nearest approach towards a flat field will be secured by playing out a moderate uniform Petzval curvature in the round sense (3) against the hollow (2), producing the recurved form (4) by superposition of the two opposing effects. This is the true and only reason why none of the existing anastigmats satisfy the Petzval theorem exactly; if well designed, they depart from fulfilment just far enough to produce the most favourable recurved form (4) for the intended normal field. A simple investigation shows that the maximum departure from the ideal flat field is then only one-quarter of the marginal departure corresponding to the secondary effect alone. The much-discussed and misinterpreted offence against the Petzval condition in modern anastigmats is thus shown neither to prove the analytical theory to be wrong nor to demonstrate that the

designer has been at fault; it is merely another case of a clever compromise, all the more creditable because it is probable that hardly one of the designers of these lenses was sufficiently acquainted with the complete theory to make proper deliberate use of it. On the other hand, it is evident that the residue of Petzval curvature always indicates a definite residual defect, for it is effective in the central part of the field and adds its share to the multitude of zonal aberrations. A particularly large residue of Petzval curvature is therefore not a thing which a discriminating designer would boast about. From this point of view it is highly significant that by far the closest approach to strict fulfilment of the Petzval condition, but still with a negative residue, is found in the Goerz " Hypergon ", with an unprecedented reasonably flat and well-corrected field of about 130°.

Of the remaining three secondary aberrations two are of a distinctively hybrid character. Of these one is ordinary spherical aberration of the primary type, but growing with the square of the distance of the image-point from the optical axis. Besides its effect on definition owing to the resulting disc of confusion, it causes the extra-axial image-points to travel towards or away from the lens according to the iris-opening, and as this displacement is proportional to the square of the distance from the centre of the field, the curvature of the latter varies with the aperture. This aberration, however, does not usually attain any really important magnitude.

The second and far more important of the hybrid aberrations represents a mixed effect of spherical aberration and astigmatism, and is one of the most serious of the residual aberrations in many anastigmats. It causes the astigmatism, or difference of focus between horizontal and vertical lines, to vary with the aperture, whilst at the same time the definition, more particularly of the vertical lines, becomes defective even at the best focus. Its presence can be detected by these criteria. Like the preceding aberration, it grows as the cube of the aperture and as the square of the distance from the centre of the field.

5*a*. **Secondary Distortion.**—This last one of the nine secondary aberrations produces radial dislocations of extra-axial image-points which are proportional to the fifth power of the distance from the centre of the field. It is usually quite unimportant, but when an unusually large amount of it is compensated somewhere near the margin of the field by an oppositely equal amount of primary distortion, then straight lines, which in ordinary pin-cushion or barrel distortion would be rendered as simple curves like fig. 18 (3), assume the recurved form (fig. 18, 4).

It is more important to note that the two forms of secondary coma which grow with the cube of the distance from the centre of the field are in that respect of the distortion type; if these forms of coma are present, the distortion will be complicated by a term varying with the square of the aperture, and this correction may become highly important when plates are to be accurately measured.

In conclusion of this section it may be pointed out that if ever means should be found for controlling the secondary aberrations, there would be found waiting for attention thirteen tertiary aberrations, mostly of the hybrid character which makes its first appearance in the secondaries. The only one of the portentous number which the author has corrected in a wide-angle lens with very beneficial results is the tertiary curvature of field; it was found possible to cause the field (fig. 18, 4) to reverse its curvature once more beyond the first cut with the ideal flat field, and thus to secure a doubly flattened field. Ordinarily the field leaves the ideal plane for good and all beyond the first cut.

The Chromatic Aberrations

All properties of lenses depend on the refractive index of the glass, and as the refractive index of every transparent medium varies for different colours, we can conclude that there must be variations of the performance of lens-systems for light of different colour.

It was shown in the discussion of the properties of a perfect lens-system that the relations of object and image depend on the location of the two principal focal points and on the equivalent focal length of the system. These relations will be identical for different colours if the focal points and the focal length are free from chromatic variation. There are thus two primary chromatic conditions, and as they are largely independent of each other, it is important to bear the distinction in mind. The freedom from chromatic variation of the principal focal points, more especially of the one on the side of the image, is referred to as " achromatism of the focal point " or as " freedom from longitudinal chromatic aberration ", whilst the desirable invariable value of the focal length is called " achromatism of the focal length " or, more significantly, " achromatism of magnification ", for it assures that different colours produce images of the same size of any given extended object.

1. **Longitudinal Chromatic Aberration.**—A simple convex lens brings blue light to a shorter focus than red light. As this

sequence of the foci in different colours is peculiar to an uncorrected lens, it is usual to call a lens or lens-system " chromatically undercorrected " when the blue focus is found closer to the system than the red focus, and " chromatically overcorrected " when the sequence is reversed.

The correction of this aberration depends on John Dollond's discovery (about 1758) that, inasmuch as lenses of flint-glass produce relatively more chromatic aberration than lenses of crown-glass, it is possible to find such a combination of a strong convex crown-lens with a weaker concave flint-lens that their opposite chromatic aberrations neutralize each other and thus remove the defect.

In the presence of remnants of longitudinal chromatic aberration there results a confusion of the rays in the vicinity of the best obtainable focus and a certain loss of sharpness in the image of a white point of light. Photographically it is of even more importance that the best photographic focus will differ from the best visual focus, because photographic plates (with the exception of heavily screened isochromatic ones) are chiefly sensitive to blue and violet light, whilst the human eye is most sensitive to yellow-green light. The visually sharpest image will thus produce a decidedly diffused photographic image, and the lens-system is described as having a difference between the visual and the "actinic focus". If of sufficient magnitude, the " actinic focus " shows itself in ordinary photographic practice with a properly adjusted stand-camera in this way: if a certain object has been sharply focused on the ground-glass, a more distant object will be sharp on the negative if the lens is chromatically overcorrected, a nearer object in the case of an undercorrected lens.

2. **Achromatism of Magnification.** — Photographic lenses, more particularly those of unsymmetrical design, may produce the different coloured images accurately in the same plane and yet of different size. If considerable, this defect will show itself, when our postulated test-object is employed, by coloured edges on the vertical lines in the outer parts of the field. When the actual lines are white on a dark ground as advised, then red or yellow on the side towards the centre of the field, and blue on the other side of each line in the image, will indicate that the blue images are larger than the red. With black lines on a white ground the interpretation will be reversed. Very small amounts of this aberration will cause serious trouble in the case of photomechanical three-colour work, and the design of lenses for that process is rendered very difficult by the high demand as regards achromatism of magnification.

3. **Secondary Chromatic Aberrations.**—The most important of the secondary chromatic aberrations is the so-called *secondary spectrum* of all ordinary "achromatic" combinations. When spectra of the same total length are produced by a crown-glass prism and by a flint-glass prism, it is found that in the flint-glass spectrum the red end is very sensibly shorter and the blue end correspondingly longer than in the crown-glass spectrum. The result is that when the two prisms are opposed to each other, so that the dispersion for extreme red and extreme violet is neutralized, there remains a residue of deviation for the middle of the spectrum in the direction of the crown-glass deviation, or a *maximum* of residual deviation for the central colours. In achromatic lenses this leads to a minimum of focal distance for the central colours and steadily increasing focal distances for the more remote colours. When expressed as a fraction of the focal length, the resulting differences of focus are almost entirely independent of the particular types of crown- and flint-glass used in the combination, and all ordinary achromatic lenses are therefore very much alike as regards the magnitude of the secondary spectrum effect. There are only a few kinds of special flint-glass, usually described as telescope flint or borosilicate flint, by which the effect can be substantially diminished, and lenses in which these glasses have been thus used are usually described as "apochromatic". The effect is by no means small, for in ordinary photographic objectives in which the deep-yellow light corresponding to the solar D-line is brought to the same focus as the deep-blue light corresponding to the G-line, the secondary spectrum causes a difference of focus between the bright-red C-light and the bright-blue F-light equal to one seven-hundredth part of the equivalent focal length, or to 0·02 in. in a 14-in. objective. The secondary spectrum is responsible for the necessity of different chromatic correction in lens-systems for purely visual purposes and in those for ordinary photographic use; at the present time it is becoming difficult to decide which compromise should be adopted for photographic objectives, because the use of isochromatic plates and of colour filters brings the region of maximum photographic effect much closer to the visual maximum than it was in the case of the unsophisticated dry plate, or especially in the wet-collodion plate.

On account of the inevitable secondary spectrum, a lens of long focus corrected for ordinary daylight will display a notable actinic focus when tried with the intense ultra-violet light of a long-flame arc or of a mercury-vapour lamp.

Another secondary chromatic aberration which frequently reaches serious magnitude is known as the chromatic variation of spherical aberration. When a lens-system has been brought to the best possible compromise as regards spherical aberration for one colour, then the spherical correction will as a rule be distinctly defective for other colours. Ordinary photographic objectives must have a reasonably sharp visual focus in order to allow of exact focusing, and it is therefore necessary to adopt a compromise between the spherical correction for the visual maximum in the yellow-green and that for the photographic maximum in the blue, with the curious result that the best spherical correction is found in a region of the spectrum more or less midway, of which neither the eye nor the ordinary dry plate take much notice. Owing to the secondary spectrum compromise, this region has a shorter focus than the combined yellow-green and deep blue, with the further drawback that even an isochromatic plate sensitized for the region of best spherical correction does not reap the full advantage through being out of focus. The chromatic variation of spherical aberration can be reduced by certain special forms of the constituent lenses of an objective. This was first pointed out by Gauss, and for that reason the defect is frequently described as "offence against the Gauss condition". Unfortunately the fulfilment of the Gauss condition usually leads to particularly large residuals of several of the secondary spherical aberrations in the outer parts of a large field, and is therefore only practicable in narrow-angle objectives.

Naturally there are corresponding chromatic variations of all the aberrations of oblique pencils, but none of these have hitherto called for serious attention.

It will be gathered from this condensed account of the principal aberrations which are present in photographic objectives, that every one of these remarkable lens-systems is the result of a large number of compromises, and that a sufficiently searching test must always reveal a multitude of small residuals of aberration of all the types which have been described. The real difficulty in any conscientious attempt of estimating the real merit of a particular lens lies in the fixing of the number of points to be awarded with reference to each of the numerous residuals which will inevitably be found, and in giving proper weight also to the degree of equality of illumination and to the amount of false light chiefly due to doubly reflected light from the glass-air surfaces.

CHAPTER IV

The Theory of Photographic Processes and Methods

Introduction

The primary aims of photography are three, namely (*a*) the reproduction of *figure*; (*b*) the reproduction of *tone values*, i.e. of light and shade; (*c*) the reproduction of *colour*.[1] Given a material sensitive to light, the *first* of these is, in the main, dependent only upon the geometrical and physical optics of *image-formation by lenses*, although even here, in practice, the extent to which the reproduction of detail can be carried is limited, in certain directions, by the physico-chemical structure of the sensitive materials. The *second* of these depends upon the whole sequence of the *physical and chemical processes* used in the photographic method, and is finally modified by certain psychophysical, or at least physiological, laws of sensitivity of the eye. The *third* of these, least advanced in fulfilment, depends upon the other two, but is more dependent upon the eye's power in translating different vibration-frequencies of radiation into visual sensations. To cover the physics and chemistry of these three aspects of photography we shall treat the subject under the following sub-divisions.

[1] The reproduction of motion might well have been added. However, the practical solution of this problem in kinematography depends upon the mechanical multiplication and movement of single photographs, and it is to the physics and chemistry of obtaining the single photograph that this article is limited.

Sectional Divisions

1. Sensitive Materials and Photographic Images, Visible and Invisible.
2. Colloidal Chemistry of Photographic Materials and Processes.
3. The Physical Chemistry of Negative Making and of After-treatment.
4. The Physical Chemistry of Positive Processes.
5. Sensitometry and the Reproduction of Tone Values.
6. The Reproduction of Detail and the Structure of the Photographic Image.
7. Orthochromatic and Colour Photography.

In order to show the relation of these phases of the physics and chemistry of photography to the practical technique, there is given a *flow-sheet* (fig. 1) of the normal sequence of operations involved in making a photograph. The practical issues are noted on the left, the references to theory on the right. It is assumed that the reader has sufficient acquaintance with the elementary practice of photography for this to serve as a general index to this article, which deals with reasons and principles, not with (*a*) apparatus, (*b*) formulæ for chemical operations, (*c*) details of manipulation. Directions for these are covered by the subsequent special articles, but inferences bearing on practice are noted when possible. No attempt has been made to give full references; citations are confined to selected text-books, monographs, and comprehensive articles, from which those desirous of so doing can proceed to further sources.

Section I.—Sensitive Materials and Photographic Images, Visible and Invisible

Photochemistry is the mother-science of photography. It has to deal with the production and regulation of chemical change by light, and, conversely, with the production of light by chemical change. We shall not deal, other than incidentally, with the second aspect, hence the term " photo-chemical " change will be generally limited to mean " the initiation and alteration of chemical changes by light ".

The word " light " may have either the narrower significance of the zone of visual radiant energy, or may be used in a wider sense to cover all radiant energy. Although photography has to do chiefly

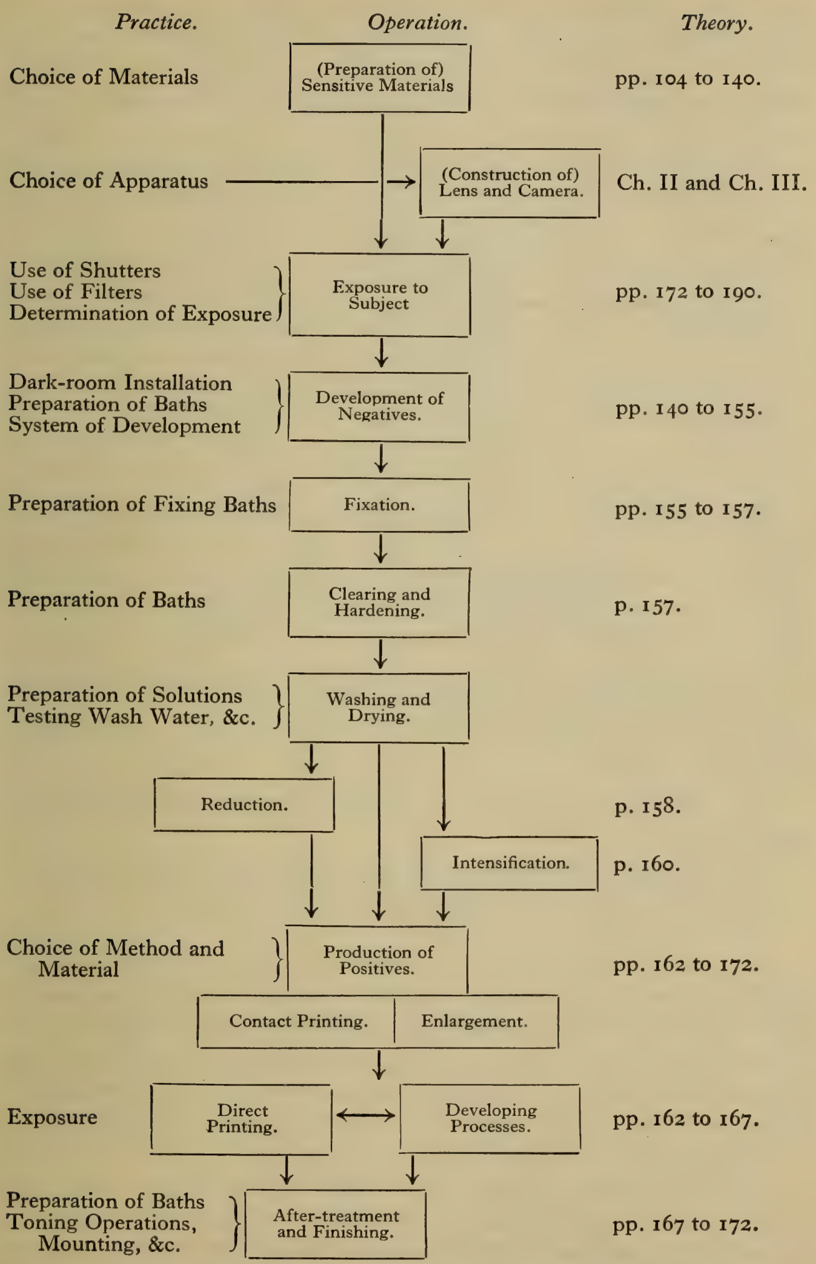


Fig. 1.—Key to the Photographic Process

with visible radiation, the photography of X-rays, ultra-violet rays, and infra-red rays is assuming ever-increasing scientific importance. The following table is given to recall briefly the gamut of electromagnetic vibrations and the regions specifically distinguished.

Region.	Wave-length.	Oscillation Frequency (Vibrations per Second).
X-rays	$0{\cdot}01\mu\mu$ to $0{\cdot}1\mu\mu$	3×10^{19} to 3×10^{18}
	$0{\cdot}1\mu\mu$ to $1\mu\mu$	3×10^{18} to 3×10^{17}
Trans-ultra-violet	$10\mu\mu$ to $200\mu\mu$	3×10^{16} to $1{\cdot}5 \times 10^{15}$
Ultra-violet ..	$200\mu\mu$ to $400\mu\mu$	$1{\cdot}5 \times 10^{15}$ to $7{\cdot}5 \times 10^{14}$
Visible	$400\mu\mu$ to $800\mu\mu$	$7{\cdot}5 \times 10^{14}$ to $3{\cdot}75 \times 10^{14}$
*Infra-red (short)	$800\mu\mu$ to 1μ	$3{\cdot}75 \times 10^{14}$ to 3×10^{14}
Infra-red (long)	1μ to 100μ	3×10^{14} to 3×10^{12}
Electric	1000μ to 1000 Km.	3×10^{11} to 3×10^{2}

Units.—The units for wave-length measurements are:

The Micron: $\mu = 10^{-3}$ mm.
The Millimicron: $\mu\mu = 10^{-6}$ mm.
The Ångstrom: Å.U. $= 10^{-7}$ mm.

* Photographically the action of radiation extends from X-rays to the short infra-red. Roughly the characteristics of the plates used are:

X-rays: Emulsions thick and rich in silver—up to 50 per cent silver bromide.
Ultra-violet: Emulsions nearly free from gelatine used in vacuo.
Red and infra-red: Emulsions sensitized with dyes.

Nearly all known chemical reactions can be induced or modified by the influence of radiant energy. Consequently photochemical effects can be observed throughout the whole field of chemistry. It is usual, however, to restrict the term to a study of those chemical changes which are started or modified more or less rapidly by radiant energy of wave-length lying within a fairly narrow range including the visual rays.

The Nature of Radiation and Light.—Two conflicting theories have been proposed to explain the phenomena of radiation. These are the emission (or corpuscular) theory and the undulatory (or wave) theory. The emission theory of Newton supposes that

luminous bodies eject minute particles, which travel in straight lines. A ray of light is the path of such a corpuscle, which is reflected from matter according to the law of elastic impact, the angle of reflection being equal to that of incidence. Reflection or refraction (transmission) is supposed to take place according to a periodicity of phase of the corpuscle, which Newton attributed to its exciting auxiliary waves in an elastic medium, the ether. Later theorists ascribed it to a polarity of the corpuscle itself. The wave theory, initiated by Huyghens in 1678, gave first place to vibrations in the ether, and this theory was revived by Young on his discovery of interference. In its earlier form, which supposed the vibrations to be longitudinal, like sound-waves in air, it was unable to account satisfactorily for either the phenomena of rectilinear propagation of light or of polarization. The difficulties were overcome when Fresnel revived a suggestion of Hooke (1672) that the vibrations were transverse to the direction of propagation. This necessitated that the ether had the properties of an elastic solid of enormous rigidity, whilst offering negligible resistance to the passage of material bodies. The elastic solid theory was displaced by the electromagnetic theory of Faraday and Clerk Maxwell. [According to this theory the vibrations are oscillatory changes of electric charge and magnetic induction, the electric force (or vector) being perpendicular to the magnetic force (or vector), and both perpendicular to the direction of propagation.] This theory was supported by the experiments of Hertz, which showed that electric waves generated by the oscillatory discharge of a condenser are propagated with the velocity of light through space.

In the last two decades, however, that rhythm or swing of the pendulum which is manifest in respect of scientific theories as in other fields of human activity has again brought forward the emission or corpuscular theory. The phenomena of electric discharge in gases and the facts of radioactivity have proved that electrically charged particles do exist and travel with velocities at least of the same order as light. The recognition of the electron as a discrete unit-element of negative electricity, but with an inertia partly if not wholly of electromagnetic origin and varying with its velocity, has modified the physical concept of matter and undermined the chemical atom. Planck showed that in order to account for the observed distribution of energy in the spectrum of a full radiator or black body—a closed cavity with temperature equilibrium inside—it is necessary to assume that radiant energy is not emitted continuously,

but discretely, in so-called quanta, such that a quantum of energy is $h\nu$, where ν is the vibration-frequency, and h a universal constant the numerical magnitude of which is $6{\cdot}5 \times 10^{-27}$ ergs sec. This idea was regarded by Planck as dependent on the atomic or sub-atomic mechanism of emission—originally of absorption. *The propagation of energy was still supposed to occur by continuous waves.* The idea of the quantum having originated in this way, it would seem that the quantum of energy must enter into the problem of the photo-electric effect, i.e. the emission of electrons by metals under the influence of light. Einstein suggested that the maximum energy of the emitted electron could not exceed the quantum for the frequency of the light, a suggestion which was soon verified. Since the energy of the ejected electron is so definitely related to the frequency of the exciting radiation, it is difficult to think that it can be derived from atomic energy as a quasi-radioactive process. The energy of the exciting radiation is disposed all over the wave-front, and it is therefore difficult to see how this energy comes to be concentrated all at one place on the emitted electron. To account for the accumulation of this energy from the incident radiation, the oscillation of the electromagnetic resonator cannot be damped, as originally assumed, and as appears essential for the explanation of dispersion and selective absorption.

The difficulties encountered by the quantum idea in the photo-electric effect were obviated by Einstein in the postulation that radiant energy not only passed out of or into matter in quanta, *but that it, itself, is propagated in empty space in discrete, undivided substantial or corpuscular quanta.* The whole energy $h\nu$ of such a light-quantum is not diffused over a wave-front, but compactly bundled up, and the defective concentration of the incident energy in the Planck radiation theory is provided for; it is evident that under these conditions the atomic resonator must either absorb a whole quantum or none.

Einstein's " light quanta " are therefore a reversion to the substantial emission theory; they not only carry energy, but mass, in proportion to their energy, according to the " relativity equation "

$$m = \frac{h\nu}{c^2},$$

where c is the velocity of light.

The quantum theory has been remarkably successful in connection with the energetics of the photo-electric effect, of black-body radiation, of X-ray emission, and, in the hands of Bohr and Sommerfeld,

in the deduction of the laws of emission of discontinuous series spectra. Its great difficulty, particularly in the rigorous form due to Einstein, is in dealing with diffraction and interference, the stumbling-blocks of the older Newtonian theory. Another difficulty with the theory is the grotesque size that the quantum assumes in free space. H. Lorentz (cited by Jeans) has pointed out that a single quantum must be considered capable of filling the several hundred square centimetre objective of large telescopes, since interference phenomena (only possible in one homogeneous quantum of light, not between independent quanta) occur on covering one-half of the objective. Yet only 1/10,000 of this extension could pass the pupil of the eye.[1]

To meet the requirements of a concentrated energy in the photoelectric effect and yet retain the essentials of the wave theory, Marx and J. J. Thomson have suggested that the energy of a wave-front is not uniformly distributed over it, but is concentrated in a few "bright specks", the residual energy being almost negligibly small, but still continuous with the specks. In J. J. Thomson's theory, this concentration is attributed to a fibrous structure of the ether, a nucleus of radiant energy or a quantum travelling as a kink along an ether-fibre, regarded as a Faraday tube of force extending between source and sink.

It is impossible at present to say whether these compromises will prove ultimately satisfactory. The quantum theory is of the greatest importance for photochemistry and photography, so far as concerns the transformation of radiant energy, and whilst we must continue to regard radiant energy as electromagnetic in nature, we are likely to find the quantum principle essential in regard to studying its conversion into other forms of energy; in fact, to quote Sir William Bragg: "For the present we have to work on both theories. On Mondays, Wednesdays, and Fridays we use the wave theory; on Tuesdays, Thursdays, and Saturdays we think in streams of flying energy quanta or corpuscles."[2]

Numerical Relations of Incident and Transferred Energy.—If E be energy incident on unit surface of a body, then from the principle of conservation of energy,

$$E = R + A + T,$$

where R is the amount reflected, A the amount absorbed, and T the amount transmitted. It is important to remember that the

[1] Compare H. Lorentz, *Physikal. Zeitschr.*, 1910, p. 355.

[2] Oxford Lecture, May, 1921.

fraction reflected may consist of either the light regularly reflected, as from a mirror, or light irregularly reflected, as from a multitude of small surfaces at all angles, the so-called scattered or diffused reflection, or both. Such scattered radiation plays a very important part in photographic theory. Absorption may be characterized as either uniform or selective. In non-selective absorption the distribution of energy through the spectrum is unaltered and the colour is not changed. In selective absorption the distribution is altered, and the colour of the transmitted light is altered. The selectivity may be slight, or, as in the case of dyes, very marked. If the percentage of light transmitted through equal thickness of a given

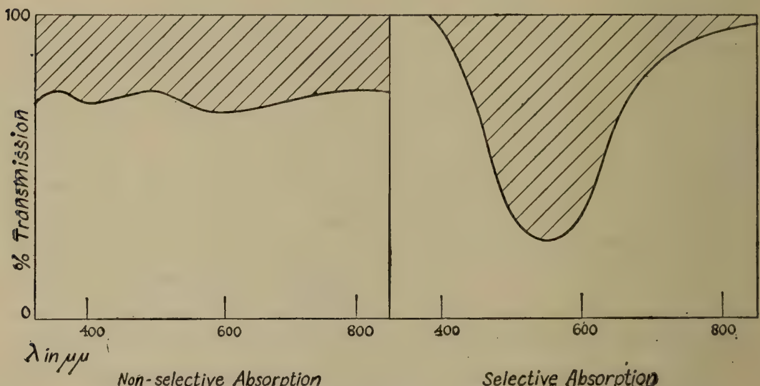


Fig. 2.—Absorption Diagrams

material be plotted against wave-length over the visible spectrum, as in fig. 2, the graph shows the more or less selective character of the absorption.

It may be noticed that although selective absorption is the primary cause of colour in Nature, yet in a great number of cases colour is due to selective scatter; this will be treated more fully later.

Quantitative Laws of Absorption.

1. *Fresnel's Law of Reflection.*—If light falls perpendicularly upon a plane surface in air the proportion of light reflected is given by the expression $\left(\frac{n-1}{n+1}\right)^2 I_o = RI_o$, where I_o denotes the incident light, and n the refractive index of the medium for light of the wave-length in question. The light which penetrates the medium is consequently given by

$$I_o(1 - R) = I.$$

2. *Lambert's Absorption Law.*—Lambert's law states that, in passing through equal layers of a material normally, equal proportions of the light which traverses them are absorbed. This means mathematically that if I is the light-energy which penetrates the boundary-surface, and I_x the energy which has escaped absorption at a depth x, then

$$I_x = Ie^{-kx},$$

where k is the *absorption-coefficient* for the wave-length of the light in question. This law suggests that the absorption of light is a molecular effect, and that each molecule absorbs a definite fraction of the light which passes by it. This idea suggests at once a law for solutions.

3. *Beer's Law.*—In solutions, the density of molecules is proportional to the concentration. Consequently the total absorption should depend upon the concentration of the solution and the thickness of the layer traversed. If m be the concentration, the law for solutions should then be given by

$$I_x = Ie^{-k'mx},$$

where k' is the *molecular absorption-coefficient*. It follows that

$$k' = \frac{\log_e I - \log_e I_x}{mx}.$$

When logs. are taken to base 10, k' is called the *Bunsen or decadic absorption-constant* or the *extinction-constant.*

Grotthus-Draper Photochemical Absorption Law.—In 1818 T. von Grotthus stated the fundamental principle for photochemical change: *Only the rays absorbed are effective in producing chemical change.* This principle was forgotten, and then revived by the American physicist J. W. Draper in 1839.

If the total thickness of the sensitive substance is d, the radiant energy of definite wave-length absorbed per second by the substance is $I_o(1 - e^{-kmd})$, where m is the concentration of the sensitive substance.

Grotthus's principle may be interpreted to mean that the rate at which the chemical change proceeds is proportional to the rate of supply of radiant energy; hence

$$\frac{dm}{dt} = pI_o(1 - e^{-kmd}),$$

where p is a constant. This may be regarded as the *normal* law of velocity for photochemical reactions, as proposed by Wittwer, and later more explicitly by van 't Hoff. In actual reactions experimentally studied there are deviations, the velocity being sometimes greater, sometimes less, than that indicated, partly in consequence of the influence of neighbouring molecules, partly from effects of reaction products.[1]

Photochemical Equivalence.—It is an evident consequence of the Grotthus-Draper law that a quantitative relation of equivalence should exist between radiant energy absorbed and the amount of substance decomposed—a relation analogous to Faraday's law of electrochemical equivalence. Such a principle has in fact been deduced by Einstein. His principle of photochemical equivalence " quantifies " Grotthus's principle in the conclusion that, *in photochemical change, each single molecule requires one quantum*, $h\nu$, *for decomposition by light* (*or radiation*). Actually in only a few cases has approximation to this result been found experimentally, the number of molecules decomposed per quantum absorbed varying from a small fraction of a molecule—implying many quanta per molecule—to some hundreds of molecules per quantum.[2] This discrepancy has been attributed to the fact that the principle was deduced on the assumption of certain ideal conditions—reversible monomolecular reaction of a rarefied ideal gas having a single nearly monochromatic absorption band of negligible width. Weigert has therefore contrasted ideal photochemical reactions, supposed to obey the Einstein photochemical equivalence principle, with *real* photochemical reactions.[3] In considering the experimental and applied side of photochemistry, it is therefore of importance to have some idea of the classification of real photochemical reactions.

Examples of Photochemical Reaction.—Photochemical change is not limited to any chemically specific type or types of reaction. It includes the simplest quasi-physical or " molecular "

[1] This expression for the rate of photochemical change is not in disagreement with the principle of mass action; it simply defines the " active mass " in accordance with the photochemical absorption law.

[2] Recent investigations directed by Nernst have shown that if the reacting molecule is coupled with a suitable " acceptor "—electrochemically, a depolarizer—the Einstein relation is approached very closely. More recently still, J. Eggert and W. Noddack, also F. Weigert (*Sitz. ber. preuss. Akad. Wissent.*, 38, 631, 641 [1921]), claim to have shown that the photographic emulsion follows the equivalence principle, one atom of silver being produced for one quantum of light of $\lambda = 408\mu\mu$.

[3] Compare F. Weigert, *Zeitschr. Elektrochem.*, 23, 357 (1917).

reactions and the most complex reactions of decomposition and synthesis. Thus we have:

TYPES OF PHOTOCHEMICAL REACTIONS

Allotropic change in elements	Sulphur $S_{rhomb} \underset{\text{Infra-red.}}{\overset{\text{light}}{\rightleftharpoons}} S_{amorph}$
Intramolecular change and Isomerization ..	Fumaric $\rightleftharpoons$ Maleic acid $\begin{matrix} COOH—C—H \\ \Vert \\ H—C—COOH \end{matrix} \rightleftharpoons \begin{matrix} H—C—COOH \\ \Vert \\ H—C—COOH \end{matrix}$
Polymerization and de-polymerization ..	Anthracene $\rightleftharpoons$ Dianthracene Oxygen Ozone $3O_2 \rightleftharpoons 2O_3$
Hydrolysis	$\underset{\text{Acetone.}}{(CH_3)_2\cdot CO} + \underset{\text{Water.}}{H_2O} = \underset{\text{Acetic acid.}}{CH_3\cdot COOH} + \underset{\text{Methane.}}{CH_4}$
Reduction	$\underset{\text{Silver chloride.}}{2AgCl} = \underset{\text{Silver.}}{Ag_2} + \underset{\text{Chlorine.}}{Cl_2}$ $\underset{\text{Ferric oxalate.}}{Fe_2(C_2O_4)_3} = \underset{\text{Ferrous oxalate.}}{2Fe(C_2O_4)} + \underset{\text{Carbon dioxide.}}{2CO_2}$
Oxidation	$\underset{\text{Lead sulphide.}}{PbS} + \underset{\text{Oxygen.}}{2O_2} = \underset{\text{Lead sulphate.}}{PbSO_4}$
Decomposition ..	$\underset{\text{Hydriodic acid.}}{2HI} = \underset{\text{Hydrogen.}}{H_2} + \underset{\text{Iodine.}}{I_2}$
Synthesis	$\underset{\text{Carbon monoxide.}}{CO} + \underset{\text{Chlorine.}}{Cl_2} = \underset{\text{Phosgene.}}{COCl_2}$

Classification of Photochemical Reactions.—This multiplicity of chemical types precludes any classification on purely chemical lines. A more successful division is obtained from consideration of (*a*) the energetics of photochemical reactions, that is, conditions of equilibrium and energy exchanges; (*b*) the kinetics of the reactions—the phenomena of velocities and accelerations. Fundamentally the former is the more important. It subdivides photochemical reactions into:

1. *Endo-actinic or energy-storing reactions*, as in the synthesis of starch by green plants from carbon dioxide and water.
2. *Exo-actinic or energy-evolving reactions*, as in

$$\underset{\text{Quinone.}}{C_6H_4O_2} + \underset{\text{Alcohol.}}{C_2H_5\cdot OH} = \underset{\text{Hydroquinone.}}{C_6H_6O_2} + \underset{\text{Acetaldehyde.}}{CH_3\cdot CHO}$$

Or, from a slightly different standpoint, into:

a. Simple reversible photochemical reactions, the reverse reaction in the dark re-forming the initial substance, thus

$$A \underset{\text{dark}}{\overset{\text{light}}{\rightleftharpoons}} B$$

b. Complex pseudo-reversible reactions, composed of one or more light and dark reactions superposed. The initial substance is re-formed over a different path

$$\begin{tikzcd} A \arrow[r] & B \arrow[d] \\ & B \arrow[ul] \end{tikzcd}$$

c. Irreversible and catalytic reactions. The primary photochemical reaction may produce a substance which then catalyses an ordinary (or dark) chemical reaction forming the product actually obtained. Again a " light " reaction and a " dark " reaction may be coupled simultaneously.

Although seeming somewhat remote from photographic application, it is obvious that reversibility is of great practical importance. A simple reversible reaction, in which the product is re-formed immediately in the dark, would obviously be useless photographically, unless means are found to prevent the reverse reaction. Again, the simultaneous coupling of reactions permits the practice of simultaneous chemical and optical sensitizing. This is referred to later.

From the kinetic point of view, photochemical reactions may be more simply classified into *direct* (primary) and *indirect* reactions. Direct reactions are initiated and maintained by light, indirect reactions by coupling with such a direct reaction. The acceleration of the indirect reaction may be due to the formation of a positive photocatalyst, or to the destruction of a negative catalyst; an example, there is reason to believe, being the union of hydrogen and chlorine in light to hydrochloric acid.

Visible and Invisible (or Latent) Images.—In the photographic plate, the products of the photochemical change which takes place on exposure cannot be seen, and the image is said to be *latent*. The latent image can be developed by its catalytic effect upon another reaction. A solution of potassium ferrocyanide, for instance, after being exposed to a light, accelerates the decomposition of hydrogen peroxide mixed with it in the dark. Likewise, chlorine exposed to light decomposes ozone mixed with it, but not in the

dark. Gaseous and liquid substances cannot, however, furnish photographic images, properly so-called, since the products will tend to diffuse, as soon as formed, from a region of higher concentration to one of lower concentration according to the Fick diffusion law. Obviously, therefore, the photo-product will tend to diffuse from regions of higher light intensity to regions of lower light intensity, thereby equalizing its distribution and preventing an optical image from forming. Although photosensitive materials for photography are necessarily solid or semisolid, this tendency of the photochemical reaction-products to diffuse plays an important part in photographic processes.

Thus it is possible that the *primary* photochemical change in a silver halide grain consists simply in an internal transfer of electrons, originally set free from internally absorbed metallic silver nuclei, and taken up by surface silver ions, which discharge to form nuclei. The *secondary* change, leading to reversal, involves diffusion of bromine from the interior to the exterior of the grain.

The Nature of the Visible and Latent Images with Silver Halide Emulsions.—Although a number of distinct photochemical reactions are used photographically, and the more important will be discussed in detail subsequently, none has such importance for this purpose as the reaction of the silver halides to light. The properties and preparation of these in photographic emulsions are noted in the next section, but it is convenient to consider here the nature of the action of light upon them and the products.

The three silver halides—silver chloride, $AgCl$; silver bromide, $AgBr$; and silver iodide, AgI—all darken in light, the degree of darkening being roughly in the order given, although actually the sensitivity depends greatly upon the mode of preparation. Scheele (1777) showed that the darkening of silver chloride in light was accompanied by loss of chlorine, and it may be considered as certain that in all three cases *halogen is split off, when a visible image is formed.* This is indirectly confirmed by the fact that *the reaction may be "sensitized" by the addition of halogen-absorbents.* In direct printing-out papers (see p. 169) this is either silver nitrate or a silver organic salt, such as silver citrate; in the direct printing silver bromide papers used in actinometers for determining exposure (see p. 185), it is usually sodium nitrite; in any case, a halogen-absorbent is effective, and in fact the darkening of the thoroughly dried halides in a vacuum is very slight and impermanent. The

nature of the dark product has, however, long been a subject of debate. The conclusion that metallic silver was formed by reduction encountered various objections, the principal one being the resistance of the image to silver solvents, such as strong nitric acid.

The suggestion was made that a subhalide of silver is formed, according to the equation

$$4Ag\begin{cases}Cl\\Br\\I\end{cases} \underset{\text{light}}{=} 2Ag_2\begin{cases}Cl\\Br\\I\end{cases} + \begin{cases}Cl_2\\Br_2\\I_2\end{cases}$$

Although it was not found possible to definitely isolate substances of this composition, nor to obtain the corresponding oxide Ag_4O, subfluoride of the composition Ag_2F was isolated by Guntz, of apparently well-defined chemical individuality; Guntz's observations were confirmed by L. Wöhler, but the argument for other subhalides remained purely one by analogy. Meanwhile the American chemist and photographic pioneer, M. Carey Lea, obtained synthetically, by various methods of combined reduction and halogenization of silver, products entirely similar to the photohalides prepared by the action of light. They showed the same variable composition as regards ratio of Ag : Hal, the same range of colour, and the same resistance to acids and oxidizing solutions. Lea concluded that the photohalides consisted of a " lake "-like combination of subhalide, Ag_2Hal, with normal halide, AgHal, in indefinite proportions, depending upon the conditions of preparation. At the same time this investigator discovered methods of preparing silver in various " soluble, allotropic modifications ", having various colours. He made the further suggestion that silver in the photohalides was present as allotropic silver. Subsequent investigation has added little on the synthetic side to Lea's brilliant solution of the nature of the photohalides, but *has shown that his " allotropic " silver modifications consist of colloid silver, and that the photohalides consist of absorption-compounds of colloid silver with silver halide.* The constitution of the photohalides and the print-out or visible image with silver compounds has become therefore a problem of colloid chemistry applied to photography, and as such is dealt with in the next section of this chapter. It will be seen that Lea not only divined the nature of the combination, in the conception of lakes, but also realized the connection of his colloid silver preparations with the photohalides.

The conflict of views as to the nature of the visible image on silver

halides became even more pronounced and diversified in regard to the invisible or latent image. Broadly, the division of opinion has been between the conception that there is a chemical change, similar in kind but differing in degree from the visible image, and the view that no actual chemical change but only a physical modification of the silver halide has occurred. We may summarize these various hypotheses as follows:

Physical theories:
1. Disintegration theory.
2. Depolymerization theory.
3. Molecular strain theory.
4. Photoelectric theory.

Chemical theories:
1. Silver germ theory.
2. Subhalide theory.
3. Colloid silver theory.

Discussing the physical theories first, the disintegration thesis, first proposed by G. Bredig, was supported by certain observations of Scholl upon silver iodide, and was regarded by Lüppo-Cramer as playing at any rate a subsidiary role in the action of X-rays on photographic plates. It supposes that light has a direct mechanical disintegrating action upon the silver halide, breaking the particles up into smaller ones, which react more rapidly with the reducing solution used as a developer. It is not in harmony with the fact that the latent image is destroyed by oxidizing agents, and the only immediate argument in favour of it was that adduced by Lüppo-Cramer. If a plate is given a liberal exposure, and then bathed in strong ammonia water, or, better, exposed to fumes of ammonia, an image is developed, due to accelerated recrystallization of the silver halide as a silver halide ammonia compound in the regions affected by light. Lüppo-Cramer explained this as due to increased solubility of the disintegrated silver halide fragments.

It has, however, been shown by the writer and Mr. A. P. H. Trivelli that practically we are dealing with the beginning of the visible image, and that the photochemical decomposition-products furnish nuclei for the recrystallization.

The *depolymerization theory*, proposed by Hurter and Driffield, supposed that light broke down larger to smaller molecular aggregates,

$$(AgBr)_m \xrightarrow{\text{light}} m\text{AgBr}.$$

It might be regarded as equally a chemical theory, but, apart from lack

of direct evidence, the modern theory of the structure of solids, derived from the X-ray analysis of crystals, leads to the conclusion that no chemical molecule, in the sense of a specially combined atom-pair Ag-Br, exists in the solid phase, but rather a space-lattice of silver ions and bromide ions, held together by the electrostatic attractions of the oppositely charged ions, in such a way that every silver ion is surrounded by six bromine ions at the corners of a cube, every bromine ion being similarly surrounded by six silver ions.

Such being the case, there is little basis for theories of change of molecular aggregation, nor for theories of molecular strain, such as that proposed by J. C. Bose, which supposed the molecule to be subjected to an elastic strain, changing its properties, e.g. making it more easily decomposed.

The photo-electric or "electron" theory of the latent image is based on the known action of light in discharging negative charges, or electrons, from many substances, notably metals, dyes, metallic sulphides, and the silver halides. The theory, so far as it has been developed, is very lacking in connecting the change effected with the behaviour of the latent image to chemical oxidizing and reducing agents. It neither explains satisfactorily why the former destroy the latent image, nor why the latter preferentially reduce the silver halide affected by light.

Of the chemical theories, the *silver germ theory* was apparently first proposed by Guthrie in 1850. He supposed that a small nucleus of metallic silver was produced by the reducing action of light, which attracted silver from the "wet plate" or physical developer then used. The comparatively great resistance of the latent image to nitric acid he explained by a "passive" condition of the silver. The thesis was revived by R. Abegg, and has not so much been disproved as transformed into the *colloid silver theory*. The subhalide theory is simply a modification of the same theory of the visible image, and the evidence for and against it in this case is of the same character. At present the most useful theory is the *colloid silver one*. According to this idea, the latent image is simply the earliest stage of the series of photohalides, consisting of colloid silver and normal halide adsorbed, a suggestion the points of which will be best dealt with in the section on colloid chemistry. *The chief argument brought against the chemical theory of the latent image is that the energy incident which makes a photographic plate developable is insufficient to produce any appreciable decomposition.*

Recent investigations have thrown considerable doubt upon the validity of this argument. Evidence has been accumulated which shows that the " sensitiveness " of an emulsion is similar in nature to the " latent image ", being destroyed by oxidizing agents under suitable conditions, and capable of restoration by reducing agents. *It appears probable, then, that the sensitiveness itself is due to the presence of colloid silver.* Two possible hypotheses present themselves in explanation of its sensitizing action. F. F. Renwick supposes that the action of light is to coagulate amicrons of colloid silver to coarser particles capable of acting as nuclei in development. The alternative appears to be a process of internal photochemical rearrangement of electrons—analogous to intramolecular rearrangement—in which electrons discharged from colloid silver are accepted by silver ions of the silver halide crystal, which themselves become reduced to metallic silver. If these " acceptor " silver ions are in the surface layer and suitably oriented, they can function as nuclei in development. It is evident that a wide variation in properties of the sensitive photohalide grains would exist, according not only to the amount of metallic silver per grain, but to its distribution. In this form a synthesis of the colloid silver and the photoelectric theories seems possible.

As already stated, the metallic silver formed by the action of light is not entirely comparable to " free " metallic silver, being adsorbed to and protected by residual silver halide, forming a photohalide of very low silver content. The distribution of this silver in the silver halide grain is discussed in pp. 127–140.

Here it may be remarked that there has been brought forward recently considerable evidence and argument in favour of the view that, in the greater number of cases of adsorption at the surfaces of solids, actual chemical combination is involved, the adsorbed layer not being more than one atom thick. Consequently it would be possible for many compounds to exist, in the solid state, of apparently indeterminate composition—since this would depend upon the ratio of surface to volume of the solid particle—and not conforming to the ordinary valency principles. It is evident that a loop-hole exists here for a modified subhalide theory to be introduced, though not involving the existence of the definite species Ag_2Hal.

Spectral Sensitivity and Optical Sensitizing.—For *ideal* photochemical reactions, that is, those following Einstein's principle of photochemical equivalence, we have the energy decomposing one molecule equal to $h\nu = \frac{hc}{\lambda}$, where c is the velocity of light and λ its wave-length. Hence it should take less and less energy to decompose

one molecule photochemically as the wave-length increases, or more molecules for a fixed amount of energy as the wave-length decreases. *Experimentally it is found, however, that if anything the contrary obtains, the sensitivity of photochemical reactions increasing not toward the longer wave-lengths but toward the shorter*, at least in the form that the number and sensitivity of photochemical reactions increases as we pass from the infra-red to the ultra-violet. *For an individual reaction*, in accordance with the Grotthus-Draper law, *it is the absorption spectrum which determines the spectral sensitivity.* It is rare, however, that the variation of the reaction-velocity with wave-length coincides precisely with the absorption-spectrum of a given component. This is due probably to the complications incident to the actual reaction, the influence of other molecular or atomic species than that considered as the primary photosensitive substance, and the influence of the reaction product or products. The best example of the relation between the absorption-spectrum and the photochemical reaction-velocity is that of the bleaching out of certain dyes in light, studied by Lazareff.

The quantitative representation of the absorption-spectrum of a given substance is obtained by plotting one of the absorption-quantities defined on p. 110 as ordinate against wave-length. This is effected by means of a spectrophotometer, a combination of a spectrometer, producing a known dispersion of incident light, and a photometer for comparing intensities through a spectrum, one-half of which is obscured by the absorbing medium, the other half being reduced in intensity by various devices, such as rotating sectors, neutral absorbing wedges, or polarizing prisms.

For photographic purposes it is seldom necessary to determine molecular absorption-coefficients; for solutions, as of dyes or coloured salts, the Bunsen or decadic extinction for 1 cm. thickness at a specified concentration is measured; for coloured glasses and films, used as light filters (p. 203), the extinction-coefficient is given without specific reference to thickness. Fig. 3 is an example of an absorption-spectrum mapped in this manner.

The spectrophotometric method involves a lengthy series of measurements, wave-length by wave-length, throughout the spectrum. It is therefore a relatively slow and tedious method, and for technological purposes various direct spectrographic methods have been devised, which reproduce integrally the complete absorption-spectrum. The simplest of these consists in the use of a wedge-shaped cell containing the absorbing solution placed in front of the slit of a

spectrograph, the slope of the wedge running in the direction of the slit. The wedge-cell used by C. E. K. Mees was a rectangular cell of 1 cm. internal length, and 5 mm. internal width, with a diagonal partition dividing it into two wedge-shaped cells. One of these is filled with the solution to be measured, the other with the solvent, usually water. The absorption of the solution is thus varied from one end of the slit to the other, from nearly zero thickness to a considerable thickness, the actual ratio from end to end being as 1 is to 15. Provided the photographic plate used is of equal sensitiveness throughout the spectrum of the light used, the photographs obtained,

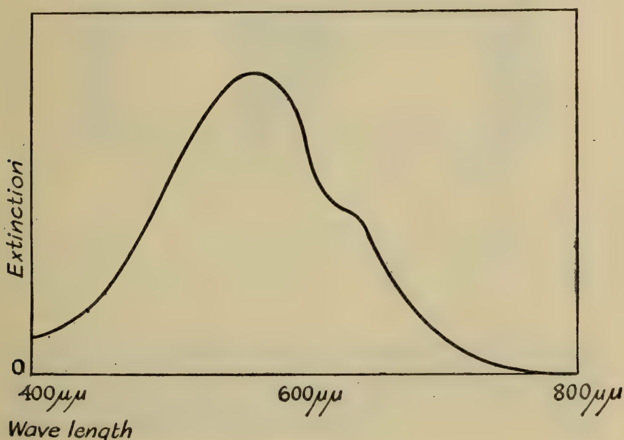


Fig. 3

taken through the wedge, will show graphically the variation in the absorption with growing thickness of coloured solution. In so far as Beer's law holds, this will also be equivalent to growing concentration. To secure uniform sensitivity through the spectrum, it is necessary to have a plate sensitive to all wave-lengths within the limits of working, and then to compensate for inequalities of such sensitiveness by special absorbing screens or filters. Thus in most of the work by Mees a panchromatic plate was used having a spectral sensitivity, as shown in fig. 5, when using a Nernst glower as light source. (The filament of a Nernst glower affords the most satisfactory method of uniformly illuminating a spectroscopic slit with light giving a continuous spectrum.) The sensitivity—the measurement of which will be dealt with directly—under these conditions is not uniform. Compensation was effected by introducing a

special screen and two cells containing solutions of mandarin-orange and *p*-nitroso-dimethyl aniline. In this way a very even

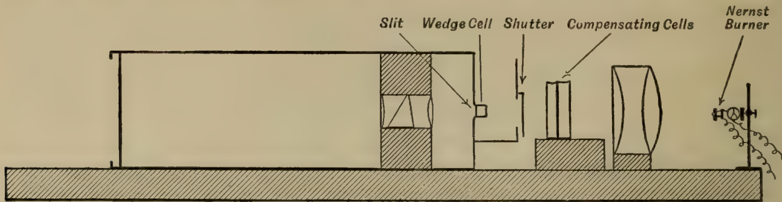


Fig. 4*a*.—Wedge Spectrograph

Fig. 4*b*.—Dye-wedge Spectrum of Xylene Red

spectrum was obtained from about 7200 Å.U. to 3900 Å.U., shading off on one side to 7500 Å.U. on the other to 3500 Å.U. A typical dye-wedge spectrum obtained in this way is shown in fig. 4*b*.

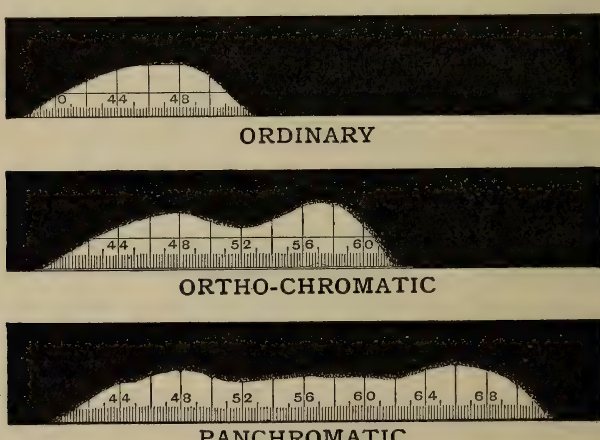


Fig. 5.—Sensitivity Curves for Plates

The *spectral-sensitivity curve* of a photographic emulsion may be obtained in a manner similar in principle to the foregoing. If in front of the slit (fig. 4*a*), uniformly illuminated by a Nernst glower, is placed a wedge of neutral, i.e. non-selectively absorbing material,

the slit will be illuminated by a range of intensities of light depending upon the gradation of the wedge. Upon development of a photo-

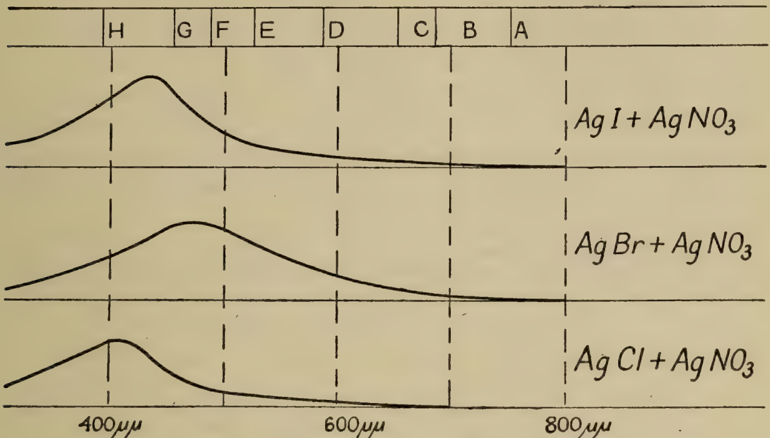


Fig. 6.—Spectral Sensitivity of Silver Halides for Printing-out

graph of this wedge spectrum, the spectral sensitivity curve of the plate is obtained. (See fig. 5.)

The spectral-sensitivities of the silver halides for printing-out

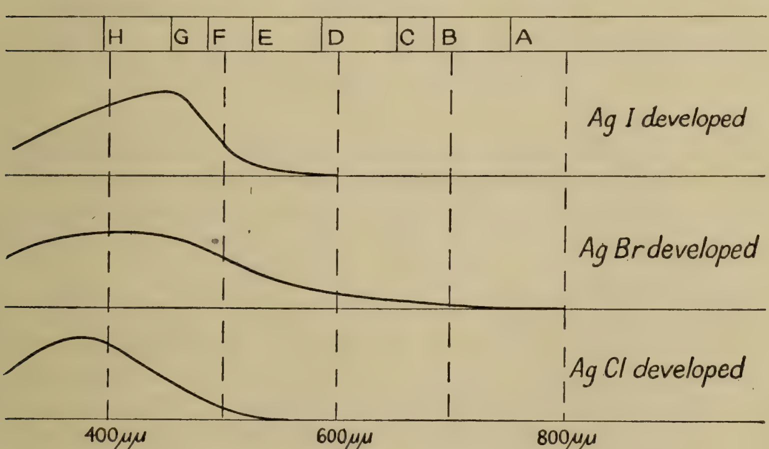


Fig. 7.—Spectral Sensitivity of Silver Halides for Development

are shown in fig. 6, and for development in fig. 7. These curves must not be regarded as absolute, since the actual spectral-sensitivity depends, for the same halide, upon its preparation, time of exposure,

and other factors. In general, however, the sensitivity falls off rapidly from a maximum in the violet toward the long wave-lengths, and again toward the ultra-violet. While the latter are of importance for many scientific purposes, the visible spectrum is of chief general importance. Vogel's discovery that treating the emulsion with certain dyes made it sensitive to the yellow and green rays therefore marked a great advance, and made what is called orthochromatic photography—the correct rendering of the relative luminosities of different colours—possible. Examples of sensitivity-curves with different sensitizers are shown in fig. 8.

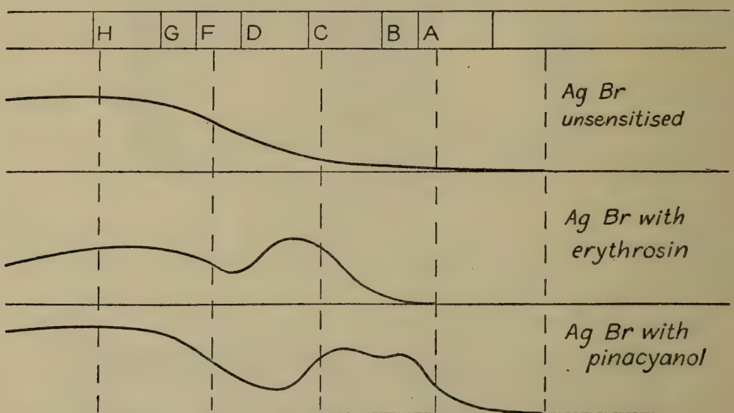


Fig. 8.—Sensitivity-curves for Sensitizer

The mode of action in such sensitizers is still somewhat in doubt. The additional spectral-sensitivity of the silver halide runs on the whole parallel with the absorption-spectrum of the dye, but with the maximum displaced somewhat toward the long wave-lengths. This displacement is probably a consequence of the dye being actually in solid solution in the surface layers of the silver halide, its absorption being modified by the changed optical density of the medium, as compared with that of other solutions. Most of the dyes which sensitize—and it should be noted that by no means all dyes are available—are themselves light-sensitive, and there is little doubt that the photochemical change of the dye is transferred to the silver halide. The three most feasible suggestions in this connection are: (*a*) the photochemical reaction product of the dye helps to decompose the silver halide, either directly or indirectly, in development; (*b*) the dye is photoelectric: on exposure to light which it

absorbs it emits electrons, which act on the silver halide, forming a latent image; (*c*) the dye has a fluorescent band in the violet or ultra-violet, which is excited to some extent by absorption in its visible absorption-band, and makes the silver halide developable. The last view would seem to contradict Stokes's law of fluorescence, according to which the emitted radiation is of longer wave-length than the exciting rays. This has been shown, however, not to hold absolutely, although generally true relatively as regards the maxima of the exciting spectrum and of the emitted spectrum.

Although "optical sensitizing", as it is called, with dyes was discovered by Vogel in 1872, the effect was really first observed in 1840 by E. Becquerel, who found in the course of an investigation of the action of the solar spectrum upon daguerrotype plates that the latent image produced by blue rays could be developed by subsequent exposure to yellow

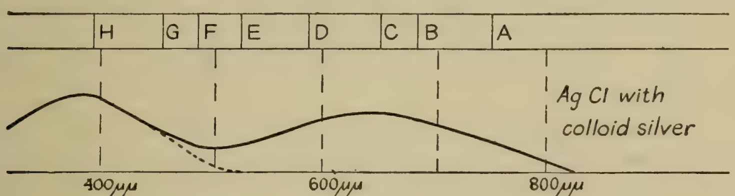


Fig. 9.—Sensitivity-curves for Silver Chloride with Colloid Silver

and red rays, or that a subsequent exposure to yellow and red, of a plate which had been given a slight preliminary exposure to blue light, allowed a latent image to be formed by the yellow and red, developable as usual with mercury-vapour. Becquerel regarded this as a consequence of the different rays having different properties, the blue and violet being "exciting" rays, the longer waves "continuing rays" (*rayons excitateurs* and *rayons continuateurs*); but the result was more correctly attributed by Vogel and Zenker to an increased absorption of the longer waves. The exact reason for this was given much later by Lüppo-Cramer, who found that synthetic photochloride, prepared by simultaneous coagulation of colloid silver with colloid silver chloride, was panchromatic, that is, showed a sensitiveness extending over the visible spectrum, as shown in the following curves due to J. M. Eder (fig. 9).

Whilst sensitizing plates for the longer wave-lengths has depended upon *addition*, the sensitizing for shorter ultraviolet rays has involved the *subtraction* of substances absorbing these rays before they can reach the silver salt. The ultraviolet sensitiveness of the ordinary silver bromide plate falls off (using a quartz optical system) very

rapidly for rays beyond 2200 A.U. V. Schumann showed that this was not due to lack of sensitiveness of the silver bromide, but to the absorption of the short waves by gelatine; by preparing silver halide layers free from superposed gelatine and exposing *in vacuo* he succeeded in greatly extending spectrography in that direction.

In the preparation of special emulsions for X-ray work, as high a concentration of silver bromide as possible is desirable, whilst the thickness should be as great as is consistent with reasonable development. Addition of heavy inert metal salts, to sensitize by secondary (scattered) radiation, has been made, but with no great effect. The chief means of reducing exposure is by the use of auxiliary " intensifying screens ", consisting of finely divided calcium tungstate compactly and smoothly spread upon cardboard or celluloid bases. The tungstate surface is placed as closely as possible in contact with the emulsion. It is excited to fluorescence by the X-rays, the fluorescent light being bluish to bluish-white, and hence forming an image. Exposure may be reduced to one-fourth to one-sixth by such screens.

The use of colour-sensitive plates, particularly of panchromatic plates, imposes greater restriction in the amount and quality of the light used to illuminate the dark room. Generally, the essential thing is adequate diffusion, not concentration, of illumination. For panchromatic plates, special green safe-lights are used, but the permissible illumination is very low. The recent discovery by Dr. Lüppo-Cramer of a desensitizing action, at very low concentrations, of certain dyes, notably pheno-safranin, has made possible great increase of illumination. A small amount of the dye in the developer enables plenty of yellow light to be used once the plate is immersed in the developer. The mode of action of these desensitizers, which do not affect the latent image, is obscure, but the method is of great promise, especially in connection with X-ray photography.

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Section II.—Colloidal Chemistry of Photographic Materials and Processes

There is probably no branch of chemistry which is of wider application to photographic processes than colloidal chemistry. In his researches on the theory of solutions the Glasgow chemist Graham discovered that certain substances in solution pass readily through certain animal membranes, such as ox-bladder, while others do not. Typical substances in solution which do not pass through these organic membranes are glue, albumen, silicic acid, &c., while substances like sodium chloride, &c., do pass through. Graham divided substances into two groups, the colloids,[1] which do not pass through membranes, and the others, called crystalloids,[2] which do. Colloidal solutions differ from the true or crystalloidal solutions in that, with suitable microscopic or ultra-microscopic apparatus, it is possible to distinguish individual particles of the " solute ", whereas it is impossible to do this in the case of the crystalloidal solutions. It is natural, therefore, to conclude that in colloidal solutions the disaggregation of the molecules has not been carried so far as in crystalloidal ones—in other words, in colloidal solutions the " solute " is present in much larger aggregates.

The colloidal condition is no longer regarded as one peculiar to certain " gluey " substances, but one into which any and every substance can be brought by suitable conditions of preparation.

Dispersoids.—Suppose a mass m of a substance of specific gravity ρ is present in the form of n grains. Such a divided substance is called a *dispersoid*, and the state of division, *dispersion*.

For spheres we have $$n \times \frac{4}{3}\pi r^3 \times \rho = m, \qquad (1)$$

and $$n \times 4\pi r^2 = S. \qquad (2)$$

[1] κόλλα, glue.

[2] This word is merely a technical term, and must not be confused with " crystal ".

The ratio, surface of dispersoid to volume of the same, is called the *dispersity*, d; thus, if S is the surface and V the volume

$$d = \frac{S}{V} = \frac{S\rho}{m}. \qquad (3)$$

When the dispersity is very high, we get *molecular dispersoids* or crystalloids; when fairly low, *coarse dispersoids*. The colloidal substances are dispersoids of medium dispersity; thus:

DISPERSOIDS

Coarse Dispersoids.	Colloids.	Molecular Dispersoids.
Diameters greater than 0·1 μ; do not pass filter paper; resolved by microscope (2000–3000 diameters).	Diameters 0·1 μ to 1 $\mu\mu$; pass through filter paper; not resolved by microcope; do not diffuse.	Diameters smaller than 1 $\mu\mu$; pass filter paper; diffusible and dialysable.

Suspensions	→	Suspensoids	→	True solutions.
Emulsions	→	Emulsoids		

The colloidal substances may also be viewed from another standpoint. The behaviour of many substances in solution can be predicted from their actual known chemical composition and physical state at a given time by applying the laws of thermodynamic equilibrium. In certain other solutions this cannot be done, but something must be known of the previous history of the solution, such, for instance, as its previous chemical treatment and physical change. Solutions to which the laws of thermodynamics may be directly applied are the crystalloidal solutions (i.e. the molecular dispersoids); those to which the laws cannot be directly applied without qualification are the colloidal solutions. It is possible that all examples of this kind may ultimately be explained on grounds of dispersion, and certain consequences of dispersion, namely, the adsorption of foreign atoms, ions, molecules, &c., at the surface of the dispersed substance.

This cannot be regarded as completely established yet, notably in respect of many organic and biocolloids, such as gums, gelatine, and glue, proteins generally, rubber, cellulose, &c., and it is possible, in particular in the light of modern theories of the relativity of space and time,

that we may have to proceed from definitions exclusively based on either alone to one which regards as " colloid " any substance or system of substances in which the rate of taking up or giving out energy is affected by quasi-frictional constraints.

Sol and Gel.—Graham also introduced two other names which have come into the literature of the subject. To the pseudo-solution of a colloid he gave the name *sol*, and to the substance after its precipitation as a gelatinous mass, the name *gel*.

Practically all photosensitive materials are either colloidal or at least form a dispersed system—of microscopically resolvable sub-division—and an important part of the photographic process consists in the proper control of dispersity, either for its direct importance in regard to light or for its indirect importance in regard to chemical and physical reactions.

Silver Halide Emulsions.—This last statement cannot be illustrated better than by reference to photographic emulsions. If we mix equivalent solutions of silver nitrate and of an alkaline halide, e.g. KCl, KBr, KI, we shall get, according to the concentration and in consequence of reactions of the type

$$AgNO_3 + KBr = AgBr + KNO_3,$$

results as follows:

Equivalent Concentration (Normal).	Dispersity.	Remarks.
0·0002	Clear hydrosol	↑ Increasing Dispersity.
0·0004	Clear hydrosol	
0·0010	Opalescent sol	
0·0025	Cloudy suspension	
0·025	Unstable suspension	
0·25	Flocculent → crumbly ppt.	
0·75	Flocculent → milky above slit → curd	
1·50	Flocculent ppt. → sandy ppt.	
3·00	Curdy → crumbly ppt.	Increasing Dispersity. ↓
4·50	Curdy → voluminous gel.	

The dispersity therefore goes through a minimum, or the grain size through a maximum, as the concentration of the reactants is

increased. This is a general law for the appearance of insoluble precipitates, attention to which was first systematically directed by the Russian investigator P. von Weimarn.[1] Representing grain-size by the reciprocal of dispersity (see equations 1, 2, 3, pp. 127–8), we shall have, on plotting values of this against concentration of reactants for silver bromide, a curve of the form shown in fig. 10.

The diagram given is for room temperature and equivalent amounts of reactants. Change of temperature and excess of one

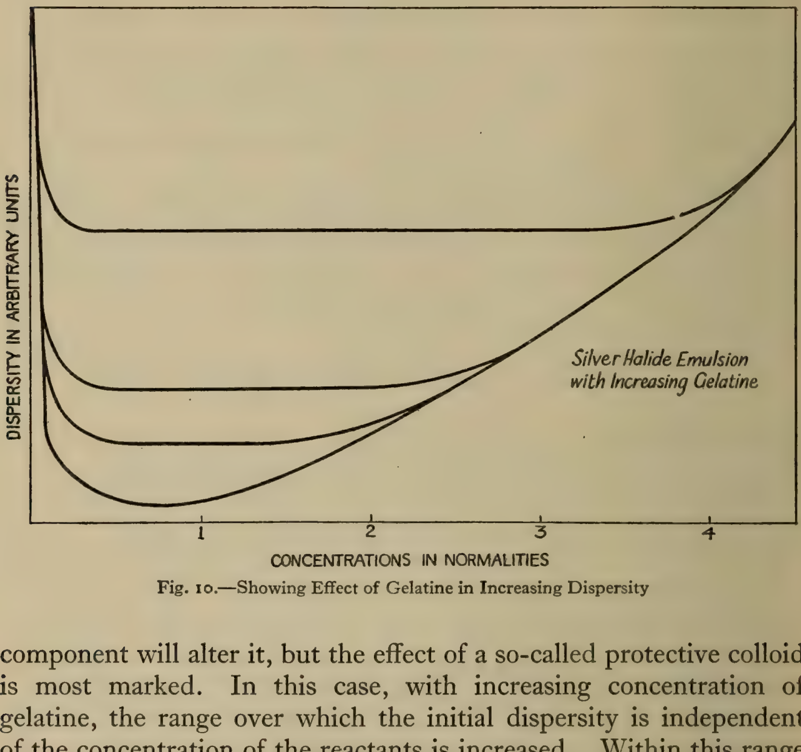

Fig. 10.—Showing Effect of Gelatine in Increasing Dispersity

component will alter it, but the effect of a so-called protective colloid is most marked. In this case, with increasing concentration of gelatine, the range over which the initial dispersity is independent of the concentration of the reactants is increased. Within this range we shall have a *nearly proportionate number of grains per unit volume*, the average grain size over the range remaining the same. *On the other hand, by varying the concentration of gelatine at initial precipitation, it is possible to materially alter the grain-size for one and the same quantity of silver halide.*

These initial conditions, which are extremely important, can

[1] According to recent work of Sv. Odèn, this result is complicated by secondary aggregation phenomena.

be further systematically varied by altering the temperature and excess of one component. In the case of emulsions for development, this will be the soluble bromide, excess of which has a solvent action on the silver bromide which increases as the temperature is raised.

Photographic Emulsions.—It is not possible here to deal with the technique of emulsion making, for which the reader may be referred to general handbooks of photography, with the caution that the methods used in the industry depart considerably from those published. *The resultant sensitive silver halide preparations*, technically termed emulsions, *are actually suspensions of the silver salt in a protective colloid medium.* They may be divided into two main classes:

a. Those in which the silver halide is formed in the presence of excess of *silver nitrate.* This includes so-called "wet collodion", still extensively used in photochemical work, collodion emulsions for printing-out, and most gelatine emulsions for printing-out. *The function of the excess soluble silver salt is chiefly that of a chemical sensitizer, as a halogen absorbent.*

b. Those in which the silver halide is prepared in presence of excess *soluble halide.* This includes both positive and negative gelatine emulsions for development. *Development emulsions for positive processes consist chiefly of silver chloride and combinations of silver chloride and bromide of very fine grain.* Conditions of precipitation already dealt with are adjusted to produce this, and the after-process of *ripening* plays no great part. On the other hand, the fundamentally important *negative emulsions are composed of silver bromide and iodide, the iodide, however, seldom exceeding a low percentage.* By *ripening* is understood a process of digestion, in the presence of excess bromide, at relatively high temperatures, a process which increases the sensitiveness and density-giving powers of the emulsion. Although there is probably some increase in size of grain effected, due to a certain growth of larger grains at the expense of smaller ones of higher solubility, this is not the chief action in ripening. The relatively coarse grain of high-speed negative emulsions is due in a greater degree to the initial conditions of precipitation, and it is not possible to convert a low-speed emulsion of the positive type into a high-speed emulsion by ripening. The chief function of ripening, which may also be effected with ammonia at low temperatures (ammonia being a solvent for silver halide), is probably to effect a combined process of partial recrystallization and incipient reduction of the silver halide to colloidal silver, in such a

way as to secure a suitable dispersion of colloid silver in the silver halide grain. These first traces of colloid silver probably act as catalyst for photochemical decomposition, though it has been recently suggested by F. F. Renwick that in high-speed negative emulsions the action of light is limited to changing the dispersity of this preformed colloid silver, coagulating it to coarser nuclei which are able to facilitate the deposition of silver on development. The silver halide grains in emulsions consist of particles ranging from ultramicroscopic dimensions—less than 0·1 μ—to grains of 3 to 4 μ in diameter (fig. 11). In the positive type of emulsions the grains are mainly ultramicroscopic to 0·2 to 0·5 μ, but in negative emulsions, whilst many ultramicroscopic grains are present, the bulk of the grains are of microscopic size, and are definitely crystallized. Whilst there is no absolute proportionality between average size of grain and sensitiveness, coarser-grained emulsions are usually faster than fine-grained ones for the following reason. The exposed silver halide grain on development, i.e. on chemical reduction, is converted to silver as a unit, independent (with certain exceptions to be noted later) of other neighbouring grains. Suppose the same amount of photochemical product (latent image) makes a large and a small grain developable, then, other things being equal, the larger grain contributes a larger amount of final product, and therefore increases the extinction-coefficient or density (see p. 111 and p. 144) to the developed image to light for the same amount of light action.[1] This factor is important, but it is not the only one, and whilst the dispersity of the silver halide in gelatine is a big factor, the dispersity of colloid silver, possibly also gelatine, in the silver halide grain is perhaps of equal importance. Further, in regard to certain photographic qualities (sensitometric characteristics) dealt with later, it is not simply the average size of grain, but the relative proportions of grains of different sizes in one and the same emulsion, which is of crucial importance. The silver bromide grains of negative emulsions are crystals of the regular system, and have been assigned to the dyakisdodekahedral class. This remains true even when a silver bromo-iodide is formed with several per cent of iodide, although the iodide itself crystallizes in the hexagonal system below 146° C. Silver iodide forms, however, homogeneous solid-solutions with silver bromide up to 30 per cent iodide, giving regular mixed

[1] This requires some kind of *concentration* of light energy related to size of grain, either in consequence of *quantum* conditions in light transmission, or to increasing amounts of photo-sensitiser in large grains.

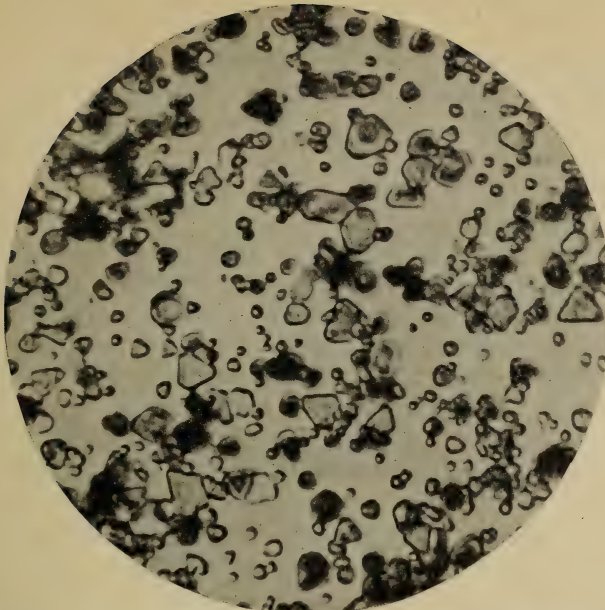

Fig. 11.—Speed Emulsion (Eastman Kodak Co.) magnified 2500 times

Showing coarse-grained structure of high-speed emulsion. Both the white crystals and the black patches are silver bromide, the latter more strongly absorbing crystals.

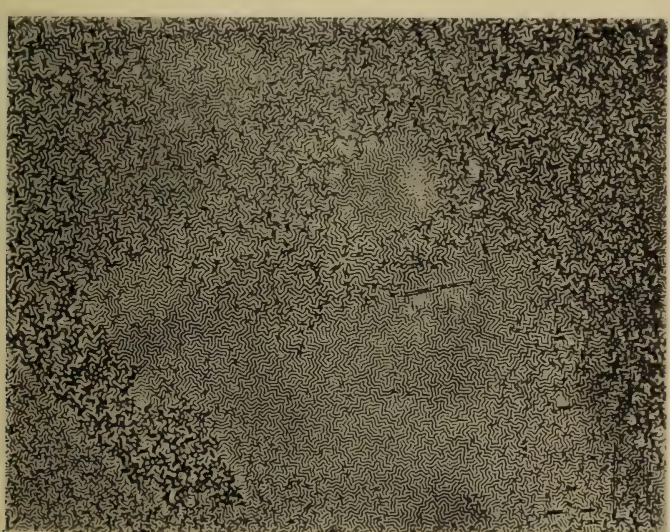

Fig. 13.—Illustrating Reticulation caused by Excessive Swelling and subsequent Hardening Action

crystals. It is possible, however, that the inclusion of the iodine ion in the silver halide lattice produces a strain causing double refraction, such as has been observed in the silver bromo-iodide crystals in emulsions. These crystal grains are for the most part tablets, flat crystals of hexagonal and triangular shape, the thickness of which is usually not more than one-fourteenth of their diameter. Since the emulsion, adhering to a rigid support, can only extend in a direction perpendicular to the support on drying and swelling, these flat grains are practically all parallel to the support. The average thickness of dry emulsion on plates and films for negative work is of the order 0·02 to 0·04 mm. By swelling in development, &c., this increases some 5 to 8 times, under normal conditions. Coarse-grained emulsions will contain grains up to 4 to 5 μ in diameter, whilst very fine-grained positive emulsions will have grains not exceeding 0·5 μ in diameter.

Colloid Silver and the Photohalides.—Colloid silver solutions or hydrosols may be prepared either by electrical disintegration —for instance by making an arc between silver poles under distilled water made faintly alkaline—or by carefully restrained chemical reduction, particularly in the presence of a protective colloid, such as dextrine or gelatine. The colour of such sols depends upon the size of the particles, passing along the scale, yellow, red, lilac, blue as the size increases, and this can be controlled by innoculating the silver solution to be reduced with varying amounts of a previously prepared sol. The more of this added, the greater the original number of nuclei or crystallization-centres on which the *same* mass of silver is precipitated, hence the finer the ultimate particles. As this has a considerable bearing upon the colour of images in positive processes, more detailed discussion is postponed to a later section (p. 166). The addition of electrolytes—salts and acids, alkalies having rather the opposite effect—to silver hydrosols coagulates the silver, the amount required being greater in the presence of strongly protecting colloids such as gelatine. Lüppo-Cramer has shown that if a silver halide hydrosol and a silver sol be mixed together, coagulated simultaneously with sulphuric acid and then extracted with strong nitric acid, photohalides are obtained identical with Carey Lea's photohalides. Reinders showed that, if silver chloride is crystallized out of ammoniacal solution in the presence of small traces of gelatine, the crystals darken more rapidly in light and contain gelatine. If they are formed in the presence of colloid silver, crystalline photohalides are formed, but this taking up of colloid

silver is inhibited if gelatine is also present. This not only confirms the view that the photohalides are colloid adsorption-compounds of silver and silver halide, but also adds weight to an earlier explanation of the function of gelatine in emulsification. Ordinary precipitated silver bromide is practically immediately and completely reduced by developers in the absence of light action. Why, then, should silver halide precipitated in gelatine resist the reducing action until exposed to light? In this connection it has been suggested that the gelatine protects the nascent silver bromide from infection by nuclei of colloid silver, each grain being isolated, whereas the precipitated mass consists of a connected gel readily taking up nuclei.

On account of the part played by protective colloids in affecting coagulation and coalescence of silver particles, we should expect differences between the images developed in collodion and in gelatine. In fact, the silver image in "wet collodion", which is built up by reduction of dissolved silver salt on the surface of the layer, is relatively very compact, and approaches mirror silver in reflecting power. Even here an influence of the *number of nuclei* shows itself, in that considerable increase of exposure (producing more nuclei) gives a much warmer toned image on development. The silver image in collodion emulsion is less compact than that in "wet collodion", but more so than that in gelatine. The normal silver image in gelatine, produced by the reduction of the silver bromide grains with relatively powerful alkaline reducers (see p. 148), is grey to black—excluding adsorption of coloured oxidation products of the developer—and it has been shown that the silver grains have a porous or spongy structure. If, however, a solvent for silver halide is present in development, more compact and finer-grained deposits are obtained. When a strong reducing agent is used, the energy of the reaction tends to break up the silver halide grain, and the whole mass is reduced, giving the spongy dark silver. If a weak or restrained reducing agent is used, the reaction tends to be confined to the surface of the silver halide, and more compact and finely divided silver results. These modifications are not only important in regard to the actual light-stopping powers and photographic qualities of the image, but considerably affect any after-treatment by chemical reagents (see pp. 158–160) such as processes of reduction, intensification, and toning. A further point in this connection is the adsorption of colouring matters by the silver image, as well as substances from the fixing bath, under certain conditions.

The Protective Colloid.—The progress of photography with

silver salts has depended in a large measure upon the displacement of albumen by collodion, and of collodion by gelatine as the protective colloid. As albumen is at present but little used, we shall not delay to consider it. Collodion and gelatine both survive, however, with the latter as the more important. The use of collodion as a photographic vehicle was apparently first suggested by G. le Gray in 1850, but the first practical prescription was due to F. Scott Archer in 1857, with silver iodide. Collodion is a solution of nitrated cellulose in a mixture of ethyl alcohol and ethyl ether. The cellulose nitrates used for collodion must have high solubility in ether alcohol, and certain other desirable properties. They are of only moderate nitration, that is, the percentage of fixed nitric acid, or of nitrogen, will not rise above certain moderate limits. Roughly, cellulose nitrates completely soluble in ether alcohol may be obtained with the percentage nitrogen varying from 10·2 to 12·8 per cent, but the solubility and viscosity cannot be gauged solely from this. A small variation of the water-content of the mixed sulphuric and nitric acids used, a change in the temperature of nitration, above all, differences in the cotton cellulose used, will produce nitrates of much the same composition but varying widely as regards such properties as solubility, fluidity of solutions, compatibility for water, character of dry film. Usually about equal parts by volume of ethyl ether and ethyl alcohol (of 90 per cent strength and upwards) are used for the solvent, and in this a good collodion cotton or pyroxylin, as it is sometimes termed, should dissolve with practically no insoluble residue. A collodion for "wet plate" work will contain conveniently about 1·5 per cent by weight of dry nitrate, and have a viscosity of ten times that of water. Neither the solution not the solvents should give a precipitate with an alcoholic solution of ammoniacal silver nitrate in twelve hours, when kept in darkness. A 1·5 per cent solution of the given viscosity will have sufficient body to flow evenly and readily over quite large plates. It should set rapidly by solvent evaporation to a transparent film; this must have sufficient mechanical strength to sustain the after-operations, but should not become horny and impermeable. Collodion solutions made from cellulose nitrate insufficiently freed from the nitrating acids tend to become more acid and lose viscosity; the stability of the solution is also affected by other conditions, as temperature, presence of chemicals, light. Whilst a certain amount—up to 5 or 6 per cent generally—of water can be added to collodion without causing precipitation, the nitrate is precipitated by large excess of water, and this method is

sometimes used for its purification. The collodion film, whilst at first readily permeable to water and dissolved substances, only swells slightly in water, differing in this from gelatine. Its protective action is considerably less than that of gelatine, and it resists acid solutions better than alkaline ones. It has no influence as a chemical sensitizer, and both for wet collodion and collodion emulsion it is customary to have an excess of silver nitrate or a silver organic salt present as sensitizer.

Collodion emulsion (see chapter "History of Photography", p. 24) would have been entirely replaced by wet collodion for photomechanical work, and gelatino-bromide for ordinary negative processes, but for the introduction of orthochromatic collodion emulsion by E. Albert of Munich in 1882. This consists of a pure collodio-silver bromide emulsion, in itself very insensitive and stable, but capable of being highly sensitized by treatment with silver eosinate before use.

Much more important as a photographic vehicle or medium is *gelatine*. This substance is prepared by the hydrolysis of collagen, the chief constituent of animal connective tissue, and forming the tissue of hide, bone, sinew, and cartilage. Its approximate composition is: C 50 per cent, N 18 per cent, O 25 per cent, H 7 per cent, but neither the formula nor the molecular weight has been definitely determined. On prolonged boiling with 20 per cent mineral acid it is hydrolyzed to a mixture of amino-acids, substances of the general type $H_2N{\cdot}[R]{\cdot}COOH$. Like these, gelatine itself is amphoteric, that is, is capable of reacting to form salt-like bodies—electrolytes—with both acids and bases. Both the acid gelatinates and the alkali gelatinates are much more strongly hydrated than the neutral gelatine, as exemplified in the curve in fig. 12 showing the swelling of gelatine in different strengths of acid and alkali.

The fact that with mineral acids the swelling goes through a maximum and then declines again has been explained by H. Proctor in terms of the repression of ionization of a salt by a common ion in excess. Most of the important physical properties of gelatine are controlled by the *hydrogen-ion concentration* of the medium. Thus its viscosity in solution shows a minimum at *p*H 4·7, its hydration or swelling shows a minimum at this point, and its chemical behaviour inverts at this point, the so-called *iso-electric point*. For values of *p*H[1] greater than 4·7 gelatine behaves as an acid, and combines with

[1] $p\text{H} = -\log\frac{1}{[\text{H}^{\cdot}]}$ where $[\text{H}^{\cdot}]$ is the concentration of hydrogen ion.

the cations of inorganic and organic electrolytes, whilst for values of pH less than 4·7 it behaves as a base and combines with anions. J. Loeb has described some very beautiful experiments illustrating this.

Whilst the hydrosol condition is of great theoretical interest and, for manufacturers of photographic materials, of great practical interest also, it is the hydrogel which concerns the photographic processes generally in operation. The transition

$$\text{hydrogel} \rightleftharpoons \text{hydrosol}$$

is reversible in a high degree, but is not sharp; so-called *melting-*

Fig. 12.—Showing Effect of Acids and Alkalies on the Water-absorbing Qualities of Gelatine

and *setting*-points depend upon the method of observation, and the melting-point of a 10 per cent jelly will be some 2° to 8° higher than the setting-point, according to the apparatus and conventions. With commercial " hard " gelatines, the setting-point of a 10 per cent jelly will be of the order 27° C., for " soft " gelatines around 22° C. The difference between the " hard " and " soft " gelatines depends chiefly upon the proportion of hydrolyzed gelatine, or gelatose. If a gelatine jelly is melted at temperatures up to about 70° C., and then cooled to the setting-point or below, its viscosity will rapidly increase till it again gels or sets. If heated above this temperature the jellying power is progressively lowered. The rate of this hydro-

lysis is increased by rise of temperature and by the action of acids and alkalies, complete hydrolysis yielding a mixture of amino-acids. The intermediate stage is variously termed β-gelatine, meta-gelatine, gelatose, and gelatine-peptone. Fish-glue, a non-setting glue largely used in photomechanical processes and made from fish-scrap, consists of substances of this character. Gelatine does not dissolve appreciably in cold water, but swells, the final degree of swelling being higher the higher the temperature, up to the melting-point of the jelly, when melting and solution occur. The influence of acids and alkalies on the swelling has already been noted; *concentrated solutions of certain salts*, such as sodium sulphate, sulphite, carbonate, and phosphate, *greatly depress this swelling*, and hence high concentrations of these are useful in developers for use under high temperature and tropical conditions, or generally where it is important not to subject the gelatine emulsion to excessive swelling. The effect of these salts is, however, only temporary. *Permanent hardening* or tanning of the gelatine, shown by reduced absorption or imbibition of water, higher melting-point of the jelly, and increased resistance to hydrolysis, is brought about by salts of aluminium, chromium, and iron; also by formaldehyde, tannins, and various quinones and quinonoid bodies. The process is quite of the same character as the tanning of the collagen of hides to leather. Tannins, as tannic acid, form insoluble compounds with gelatine, a reaction useful for the detection of gelatine in some cases, but having no application in photography. The oxidation products of many organic developers (see p. 148), notably pyrogallol, tan gelatine, hence produce *relief images*, since the tanning action is proportional to the amount of the reaction, which is itself a function of the light-action. The tanning or hardening action of the alums is due to hydrolytic separation of the alum into hydrous oxide, colloidal in character, and free acid:

$$Al_2(SO_4)_3 + 3H_2O \rightleftharpoons Al_2O_3 + 3H_2SO_4$$

(with intermediate formation of basic salts very probable).

The alumina or other oxide combines with the gelatine, either as an adsorption complex or as a compound of stoichiometric character, a point which cannot be regarded as completely settled. In any case, it is retained on washing the gelatine with hot water. This action is made of use in practice, especially where the material has to withstand relatively high temperatures or prolonged or repeated chemical treatment. Hardening with formaldehyde (formalin = 40

per cent formaldehyde, CH_2O) probably depends upon an interaction of amino-groups of the gelatine with formaldehyde and condensation to an insoluble compound. Its hardening effect, in from 1 to 5 per cent solution, is greatly increased by intermediate drying.

A gelatine layer on glass, or a photographic emulsion on a rigid support, if exposed to conditions producing excessive swelling but not causing solution, will be liable to frill, i.e. lose adhesion at the edges. In general it is necessary to "substrate" photographic supports, such as glass and celluloid film, with a very thin coating of hardened gelatine, before they are coated with the emulsion. If exposed both to excessive swelling and to tanning action, the gelatine layer becomes differentially strained beyond the limits of elasticity of the jelly, and develops a curious puckered structure, termed *reticulation* (see fig. 13, on plate facing p. 132).

Gelatine jellies dried in air retain from 8 to 16 per cent moisture. When dried in thin layers on a rigid support, as in photographic materials, the contraction on drying, like the expansion on swelling, is practically limited to the direction perpendicular to the support, and this behaviour persists in pieces of gelatine after removal from such a support. *The rate of drying is limited by the rate of diffusion of water in the gelatine layer to the evaporating surface.* Consequently it progresses more rapidly at corners and edges, and proceeds by gradual regression of a moist area to the centre of a plate or film, a circumstance which probably has some part in inducing inequality of behaviour on development over a large plate.

A practical inference from this is that when photography is used for photometric purposes, as in astronomical work, definite precautions should be taken to ensure uniform drying conditions independent of seasonal atmospheric conditions.

The rendering of gelatine insoluble, i.e. the tanning of it, by oxides of chromium is the basis of a very important group of photographic and photomechanical processes. These are *the carbon process*, in which a pigment is suspended in gelatine sensitized with bichromate of potash, the *bichromated fish-glue process* used in the half-tone reproduction process, and various photo-engraving and photo-relief processes. All of these depend upon a differential change of properties of the colloid, due to the progressive reduction of bichromates to chromic oxide in light (see p. 171). In the carbon process, it is the change of solubility in hot water; in the fish-glue process the rendering of the colloid insoluble in cold to warm water, the remaining colloid (where exposed to light) being baked so as to resist acids; in photolithography, the reduced imbibition of the light-affected parts, permitting a correspondingly stronger adher-

ence of a greasy ink. To these must be added a group of indirect bichromate processes, derived from *ozotype*, in which the oxide causing the insolubility of the colloid is not produced by direct photolysis, but indirectly by reaction with an intermediate silver image.

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SECTION III.—THE PHYSICAL CHEMISTRY OF NEGATIVE MAKING AND OF AFTER-TREATMENT

Development and Developers.—The primary operations in the production of a negative with silver halide preparations are *development* and *fixation*. Development is, chemically, a *reduction process*, consisting in the conversion of ionic into metallic silver. Technically, the complete solution is the developer, and development is divided into (*a*) physical development and (*b*) chemical development. The term physical development is applied to any process in which the image is built up by silver obtained from the developing solution. *Physical development*, as employed in the "wet collodion" process, and in certain special processes, consists in the use of *an acid reducing agent in conjunction with silver nitrate solution*. Generally a mixture of silver nitrate and acid ferrous sulphate is used, the acidifier being acetic acid. The chemical reactions involved are:

$$6Fe_2SO_4 + 6AgNO_3 = Fe_2(SO_4)_3 + Fe_2(NO_3)_3 + 3HNO_3,$$

or in terms of the ionic theory

$$\dot{Ag} + \ddot{Fe} \rightleftharpoons \underset{\text{(met.)}}{Ag} + \dddot{Fe}.$$

The metallic silver thus formed reinforces the latent image.

The function of the organic acid is to act as a regulator or "buffer". Ferrous and ferric acetates are less dissociated than the iron salts of mineral acids, hence ferrous ions are fed more slowly to the zone of reduction. The reaction is reversible, but it is probable that the presence of organic acid tends to make the reaction, on the whole, one of reduction.

Chemical development, as used with gelatino-silver bromide emulsions, involves the use of stronger reducing agents which *form the silver image from the silver halide grains affected by light.*

In the development of "wet collodion" by physical developers, the image is built up on the top of the layer, and it is apparently the relative degree of nucleation[1] per grain of a thin upper layer which counts in starting development, rather than the number of grains just made developable. On the other hand, in chemical development the image is built up in the film, without auxiliary silver deposition, by reduction of individual light-affected grains, so that *the number of grains* which are *light-affected per unit volume* of the emulsion layer, and *the size of the individual grains* are of primary importance in building up the image. In fig. 14 is shown quite diagrammatically the way in which the image grows in development by growth in size of the developed grains; whilst in fig. 15 are given photomicrographs of sections of a developing layer, taken for different times of development and for different exposures (F. E. Ross).

The microscopic study of development leads to the following conclusions. With constant time of development and increasing exposure, the number of grains developed increases with the exposure. For the shorter exposures the developed grains are chiefly near the surface, and as the exposure increases the lower layers fill up with more developed grains. *With constant exposure* and increasing time of development the number of grains brought to development soon reaches a limit, but the grains continue to increase in size to a limit. This means that the reduction of a grain to metallic silver is not an instantaneous process but takes time. Also it is rare for the symmetrical crystalline grains to retain their shape on reduction; usually the grain is distorted and to some extent disin-

[1] This phrase means number and disposition of nuclei per grain.

tegrated, and in the long exposures where the packing of affected grains is close, grains tend to run together and form secondary structures. The size of the silver grains varies with the emulsion, being of the order 0·0005 to 0·004 mm. in diameter.

The size of the silver grains is of importance in spectroscopy and astronomical photography, and will be referred to again (see p. 196).

Whilst little affected by ordinary variations of development,

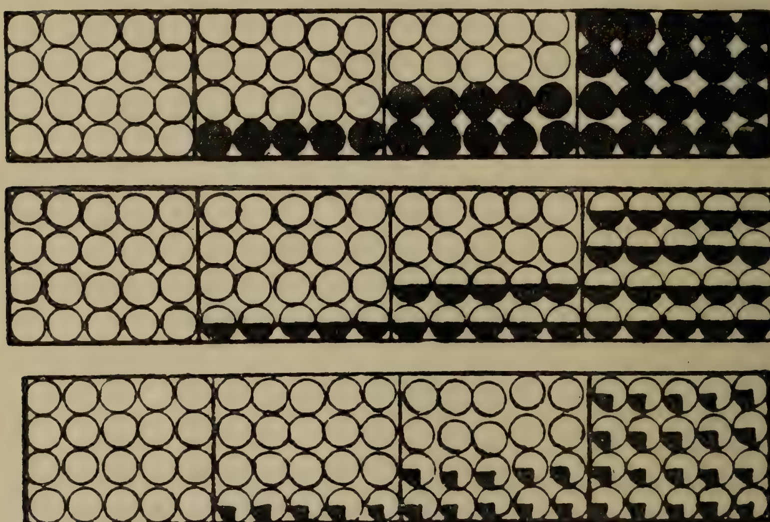


Fig. 14.—Progress of Development of Four Tones: Three Stages of Development (A. Watkins)

1, One-quarter developed. 2, One-half developed. 3, Completely developed (to D_∞).

certain special developers containing solvents for silver halide tend to give a finer-grained deposit, notably *p*-phenylene-diamine. Such developers form an *intermediate type* between physical developers with added silver and typical chemical developers, it being understood that the distinction between physical and chemical development here is a matter of photographic terminology.

Classification of Developing Agents.—The developing agent or reducing agents proper may be subdivided into inorganic and organic developers, or again into acid and alkaline developers, according to the reaction of the solution. Neither of these divisions is very satisfactory, as the same substance might be placed in either group in certain cases. For convenience we will list a number in

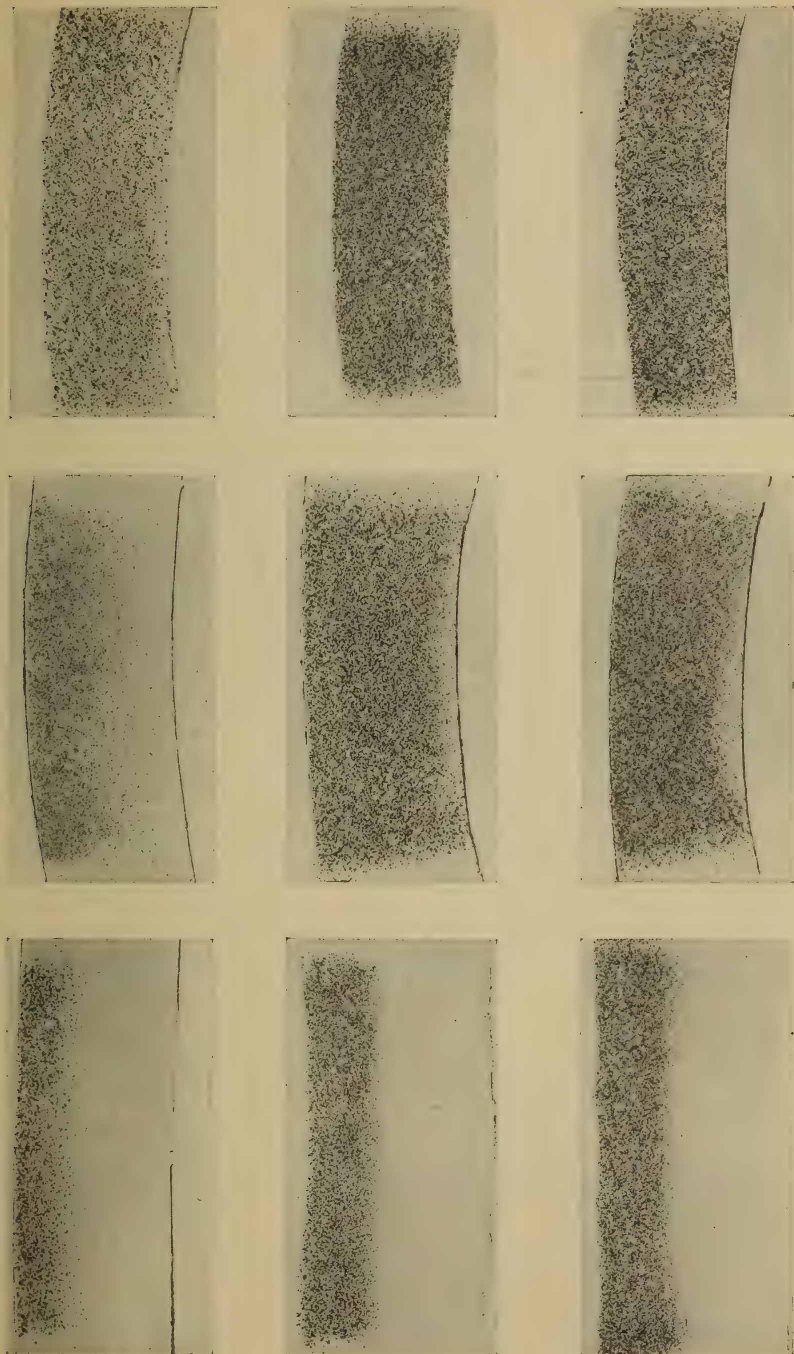


Fig. 15.—Photomicrographs showing effect of Exposure and Development in producing Silver (F. E. Ross)

Facing p. 142

this way, before noting more appropriate specifications following their photographic behaviour.

Acid.		Alkaline.	
Inorganic.	Organic.	Inorganic.	Organic.
Ferrous fluoride ($FeFl_2$).	Pyrogallol.	Hydrogen peroxide (H_2O_2).	Pyrogallol.
Ferrous oxalate (FeC_2O_4).	Amidol.	Hydroxylamine (NH_2OH).	Hydroquinone.
		Hydrazine (N_2H_4).	*p*-aminophenol.
			o-aminophenol.

Several of those cited have only a theoretical interest. Thus ferrous fluoride is a purely inorganic developer which develops silver bromide in weak acid solution. Although impracticable owing to the presence of hydrofluoric acid, it is interesting in applications of the ionic theory to photographic chemistry. According to this theory, ferrous salts of most mineral acids, such as $FeCl_2$, $FeSO_4$, cannot develop silver bromide because in the reversible reaction $\ddot{\mathrm{Fe}} + \dot{\mathrm{Ag}} \rightleftharpoons \dddot{\mathrm{Fe}} + \mathrm{Ag}$ (met.), the reaction with the lower sign tends to preponderate, given the low concentration of silver ions afforded by silver bromide, and a silver solution sufficiently supersaturated to deposit metallic silver on the latent image cannot be formed. Anything removing ferric ions will help to push on the reaction with the upper sign, and as ferric fluoride is less dissociated than ferrous, the removal of ferric ions can be secured with fluoride ions. However, since both ferrous and ferric fluoride form complex ions, it is possible that the actual reaction is

$$\begin{array}{l}\mathrm{NaFeFl_3}\\ \swarrow\\ \mathrm{FeFl_3}''' + \dot{\mathrm{Ag}} \rightleftharpoons \mathrm{FeFl_3}'' + \mathrm{Ag}\ (\mathrm{met.}).\end{array}$$

Such complex ion formation is still more evident with ferrous oxalate, which only develops in presence of excess of potassium oxalate. It forms the double salt $K_2Fe(C_2O_4)_2$, which readily dissociates thus:

$$K_2Fe(C_2O_4)_2 \rightleftharpoons FeC_2O_4 + K_2C_2O_4.$$

The developing ion is $Fe(C_2O_4)_2''$, and the solution has a reddish-

yellow colour, in contrast to the pale-green to colourless tint of normal ferrous salts. The reaction in development is

$$(C_2O_4)'' + Fe(C_2O_4)_2'' + \dot{Ag} \rightleftharpoons Fe(C_2O_4)_3''' + Ag \text{ (met.)},$$

and is reversible. If ferric oxalate in large amounts is added to this developer, reduction of silver bromide can be inhibited. Ferric oxalate and potassium bromide in solution will bleach the silver image to silver bromide, and working in this way an equilibrium in photographic development was quantitatively determined.

Quantitative Study of Development and Rate of Development.—Before passing to consideration of the more complex organic developers in general use, the methods of dealing with development quantitatively must be considered. The rate of a chemical reaction is usually measured by the quantity of substance changed per unit time. The *substance of chief interest here is the silver transformed from the ionic to the metallic condition.* Ordinary analytical methods would obviously be very inconvenient, and at the same time give no necessary connection with the optical and photographic properties of the developed image. Although important pioneer attempts to obtain quantitative relations between the amount of chemical action produced by light and development, on the one hand, and the optical properties of the developed image, on the other, were made by Sir W. de W. Abney and others, quantitative methods capable of precision and a satisfactory terminology were first introduced by F. Hurter and V. C. Driffield. They defined the *opacity* of a photographic image as the ratio of the incident (normal) light to the emergent light, and *transparency* as the reciprocal of this. The (Briggs) logarithm of the opacity is called *the density.*

The value of the transparency is measured photometrically. It will be seen that the *density* D, defined as the logarithm of the opacity, is the same as the *extinction-coefficient* already mentioned in connection with the absorption of light (see p. 110). Further, they showed by experiment that the density thus defined and measured photometrically is proportional to the mass (M) of metallic silver per unit area on a negative, that is, $D = pM$, where D is the density and p a constant. This relation has been confirmed by other observers, although the constant p, *termed the photometric constant*, varies to some extent with the developer, and may very possibly be found to vary somewhat with other con-

ditions of development. They further introduced the picture of the photographic properties of a plate by plotting a so-called *characteristic curve*, in which the *densities* are taken as ordinates against the corresponding values of $log_{10}E$ as abscissæ, E being the *exposure* (fig. 16), i.e. the intensity of light multiplied by the time of exposure.

This curve shows, disregarding for the present any descending portion on the right beyond the maximum, three fairly well defined

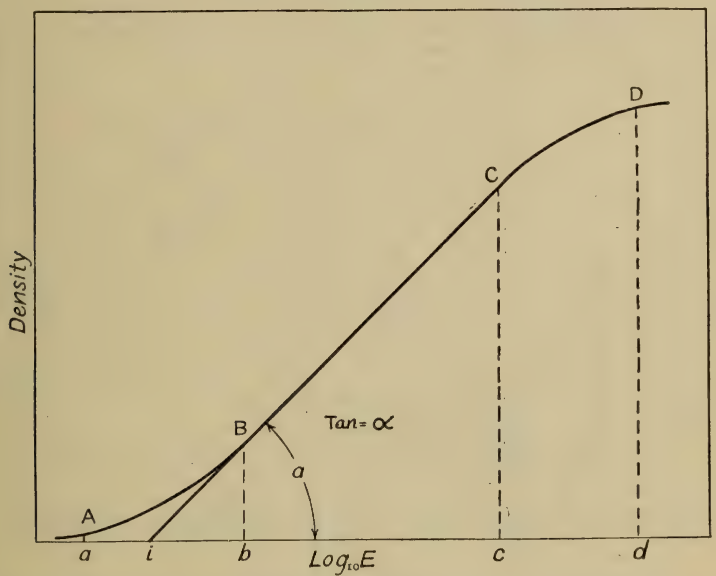


Fig. 16.—Typical "Characteristic Curve" for a Plate showing the "Development Factor" or "Contrast Factor" γ

regions: the initial part, convex to the $\log_{10}$E-axis, termed the *region of under-exposure* (for reasons discussed later); the middle part, approaching more or less to a straight line, termed the *region of correct exposure*; and the upper part, concave to the $\log_{10}$E-axis, termed the *region of over-exposure*. Without considering for the present the complete curve, it is evident that over the straight-line portion, $dD/d \log_{10}E$ is constant (γ), and this constant, the slope of the characteristic curve in the straight-line portion, is called the *development factor*. Over the region considered, it measures the photometric contrast of the negative, and, provided no selective light-absorption exists, the photographic printing contrast of the

negative also. The value of γ increases with time of development, the increase tending to a limit, termed γ_∞ (gamma infinity), which measures the extreme contrast of which a plate is capable. We shall return to the significance of these quantities for photographic printing and reproduction later (see p. 187); meanwhile we may note that the straight-line portion of the characteristic curve can be represented by an equation of the form

$$D = \gamma(\log_{10}E - \log_{10}i),$$

where E is the exposure (intensity of light $\times$ time) to light, γ is the

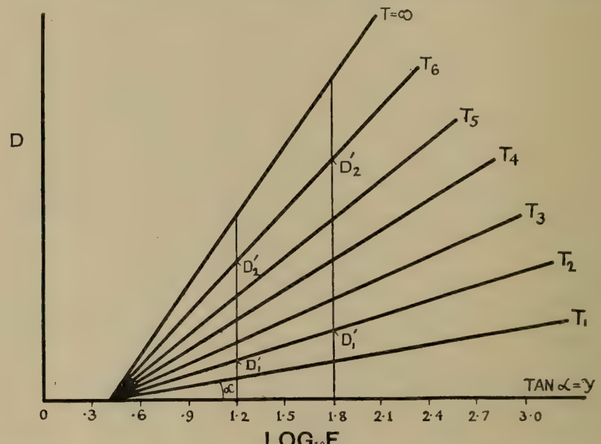


Fig. 17.—Showing Effect of Time of Development on the Development Factor ($\tan\alpha$)

development factor, i.e. $\tan\alpha$ in fig. 16, and i is a constant, the exposure at which the straight line cuts the axis. Although this equation can only be regarded as an approximation it is a very useful one, furnishing a reference standard for the phenomena of both development and exposure. It will be seen that so long as this equation holds, for different degrees of development, $D = k\cdot\gamma$, E being constant, that is, any function representing change of *density* with *degree of development* will be true also for gamma. This is expressed in Hurter and Driffield's *Law of Constant Density Ratios*. The normal manner in which the density and gamma change with time of development, if this law holds, is represented in the diagram (fig. 17).

The characteristic curves intersect at a point ($\log_{10}i$) on the $\log_{10}E$-axis. The value of γ increases with time of development, but less

and less as development proceeds, and ultimately reaches a limit which is characteristic of the plate, but also depends to some extent on the developer. If we now develop (for different times) plates which have been given a series of exposures increasing in geometric proportion, measure the densities and plot the resulting curves, and then plot γ (or density D) as a function of time, we get a curve of the type shown in fig. 18. It will be seen that γ (and density) increase rapidly at first, then more slowly, finally reaching a limit.

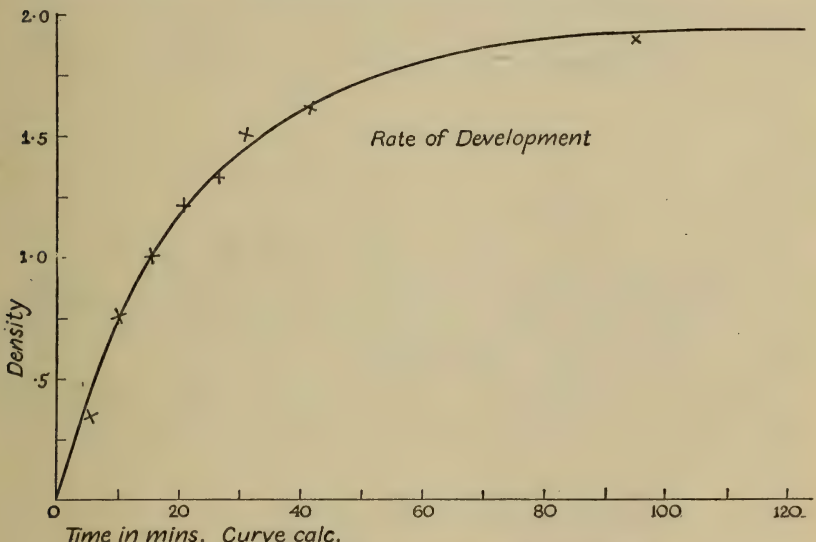


Fig. 18.—Showing Rate of Development of Photographic Plate

The Velocity of Development.—Making certain simplifying assumptions, the mathematical function representing this curve can be obtained. Let us suppose, in agreement with the approach of the curve to a limit, that D_∞, the limiting density, corresponds to the total developable silver bromide for any fixed exposure. The density undeveloped at any time t will be $D_\infty - D$, where D is the density developed at time t. Supposing other factors—such as the concentration of the developer in the film, its rate of diffusion, temperature, &c.—constant, we can then put the rate of development, $\frac{dD}{dt}$, proportional to the " undeveloped " density, i.e.

$$\frac{dD}{dt} = k(D_\infty - D),$$

where k is a constant. This equation gives on integration

$$k = \frac{1}{t} \log_e \frac{D_\infty}{D_\infty - D} = \frac{1}{t} \log_e \frac{\gamma_\infty}{\gamma_\infty - \gamma},$$

$$\text{or} \quad D = D_\infty(1 - e^{-kt}); \quad \gamma = \gamma_\infty(1 - e^{-kt}).$$

These equations agree very well with the experimental facts. The constant k is termed *the velocity-constant of development.*

This curve represents the behaviour of ferrous oxalate, fluoride, and citrate fairly well, but is not universally applicable over a long range. It has been shown by A. Nietz that an empirical modification, giving the form

$$\frac{dD}{dt} = \frac{K}{t}(D_\infty - D),$$

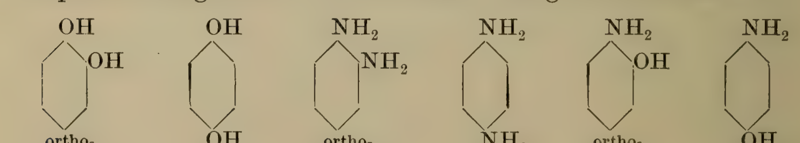
$$\text{or, integrated,} \quad K(\log_e t - \log_e t_o) = \frac{D_\infty}{D_\infty - D},$$

has a wider range of application. *The constant k* (*or* K) *is proportional to the active mass of the reducing agent*, but to make this precise we must consider the composition of alkaline organic developers and the function of the constituents.

Alkaline Developers.—The usual developing solution consists of an organic reducing agent, an alkali, and an alkaline sulphite, as, for example, in the typical formula:

Pyrogallol is the reducing agent.
Sodium carbonate is the alkaline accelerator.
Sodium sulphite is the stain preventative.
Water is the solvent.

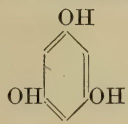
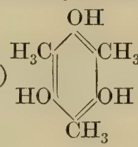
The organic reducing agent is the actual reducer; practically all organic developers are aromatic derivatives, and restricted to *ortho-* and *para-* diphenols, diamines, or aminophenols; the *ortho-* and *para-* arrangement of the molecules being as shown below.



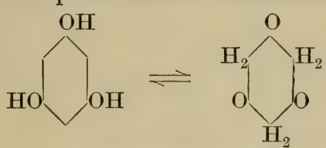
ortho- (hydroquinone) — para- (hydroquinone) — ortho- (*o*-phenylene diamine) — para- (*p*-phenylene diamine) — ortho- (*o*-amino- phenol) — para- (*p*-amino- phenol)

Instead of a benzene nucleus, we may have a naphthalene nucleus, and various other substituents may be introduced, with definite

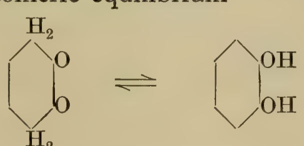
effects on the developing properties. The reason for this general rule for the structure of organic developer is not quite certain. It was attributed to the difficulty of formation of metaquinonoid oxidation products, but Homolka finds that while symmetrical trioxybenzene is not a developer, it becomes one if the trimethyl body is formed:

(not a developer)  (developer) 

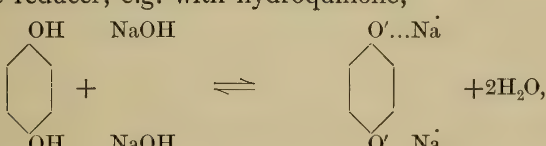
and this he attributes to prevention of tautomeric change of the type



This brings us to the function of alkali. With increase in concentration of alkali—better still, with increase in concentration of hydroxyl ion OH′—the velocity of an organic developer increases to a maximum. This is probably to be attributed to, firstly, displacement of the tautomeric equilibrium



to the right (keto → enol), and next to the formation of ionized salts of the reducer, e.g. with hydroquinone,



the actual reducer being the ion $C_6H_4O_2''$.

This view regards the reducing agents as pseudo-acids, with very small ionization constants, but forming strongly dissociated salts (Hantzsch). Values of the ionization constants have been obtained for several developers.

An alternative explanation is to suppose that all reducers act by decomposition of water:

$$R + H_2O = RO + 2H,$$

the true reducing agent being hydrogen, probably as *atomic* hydrogen, the concentration of which will be inversely as that of the hydrogen ion, therefore directly as the concentration of hydroxyl ion, according to the equilibrium

$$\dot{H} + OH' \rightleftharpoons H_2O.$$

It will be seen that if this conception of reduction by atomic *hydrogen* be accepted, or even regarded as equivalent to that of direct interaction, then the *intensity-factor* of chemical change in development, that is, the *chemical reduction-potential* of the reducing agents, might be regarded as (atomic) *hydrogen pressure*,[1] and developers graded in a scale of *reduction-potentials* corresponding to equivalent hydrogen pressures generated in aqueous solution under corresponding conditions. These equivalent conditions would be equivalent concentrations of active ion, and equal free alkali (hydroxyl ion) concentration. We have not at present sufficient knowledge of the state in solution of organic developers to decide these questions.

The Function of Sulphite and Following Reactions.— All the organic reducers used as developers tend in alkaline solution to rapidly absorb aerial oxygen, giving coloured oxidation products of a complicated nature, generally yellow to brown in colour. This not only rapidly lowers the efficiency of the developer, but the colouring substances stain the gelatine, and give poor negatives. Alkaline sulphites, such as Na_2SO_3, introduced by Berkeley, very largely prevent this action, and enable stainless negatives to be produced. The chemistry of this effect has not yet been completely cleared up. It was at one time supposed that preferential oxidation of the sulphite to sulphate took place, but it has been shown that sulphite actually reacts with the primary oxidation products of the reducer (which are of a quinonoid character, and readily react further, forming complex condensation products), forming derivatives of the initial reducer which themselves have reducing power. Thus with hydroquinone, the primary oxidation product of which is quinone, it is probable that sulphite interacts with the quinone, forming hydroquinone sulphonate. It is to be remarked here that the primary oxidation products of the developer are not stable in the presence of alkali, i.e. of hydroxyl ion. Simultaneous reduction of the quinonoid body and substitution of hydroxyl in another molecule of quinone appears to take place. In consequence

[1] The pressure which would be set up by the hydrogen atoms, regarded as a gas.

of these reactions, alkaline developing solutions do not form true equilibrium systems in reduction.

Since sulphites dissolve the silver halides to some extent—silver iodide negligibly, silver bromide slightly, silver chloride freely—it is possible for the sulphite to superpose a certain degree of semiphysical development upon the normal chemical development. This action is very slight with silver bromo-iodide emulsions used in the negative process, but plays a preponderant rôle in the development of positive emulsions of silver chloride and chlorobromide (see p. 163). Further, as sodium sulphite is hydrolyzed in solution, it behaves as a weak alkali, comparable with carbonate.

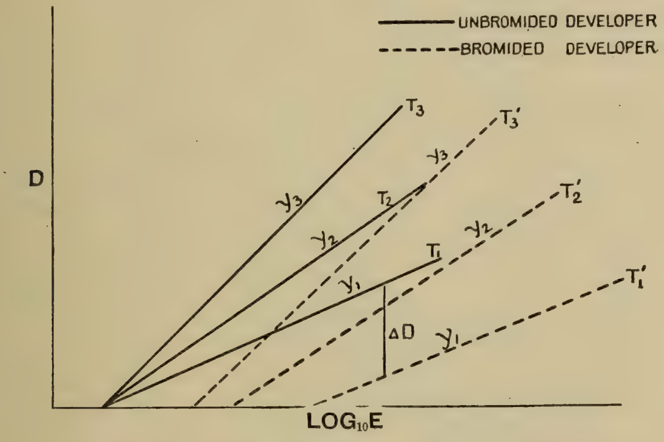


Fig. 19.—Showing Effect of Bromide on Characteristic Curves

Restrained Development and the Function of Bromide.—Many developing formulæ, particularly with very "energetic" reducers, include, in addition to the *reducer*, the *accelerator* (alkali), and the *preservative* (sulphite), a certain small amount of a *restrainer*, the last being practically always potassium bromide. The use of soluble bromide as a restrainer and to diminish chemical "fog" antedated Hurter and Driffield's researches, but they first showed the rationale of its action. This is most clearly shown by a diagram such as fig. 19, showing the progress of development with time in a bromided and unbromided developer respectively.

Comparing these in respect of the families of curves obtained on development for different times, it is found:

(*a*) In absence of bromide, or silver halide solvents, the curves

(more precisely, the straight-line portions) intersect at a point on the $\log_{10}E$-axis (fig. 17).

(*b*) In the presence of bromide in sufficient concentration the curves intersect at a point below the $\log_{10}E$-axis (fig. 20).

The effect of bromide, at the same concentration, varies from one developer to another, but is constant and very characteristic of developers individually. Sheppard and Mees made use of this effect to compare different developers (reducing agents) with respect to their energy, or reduction-potential. For every developer, over a

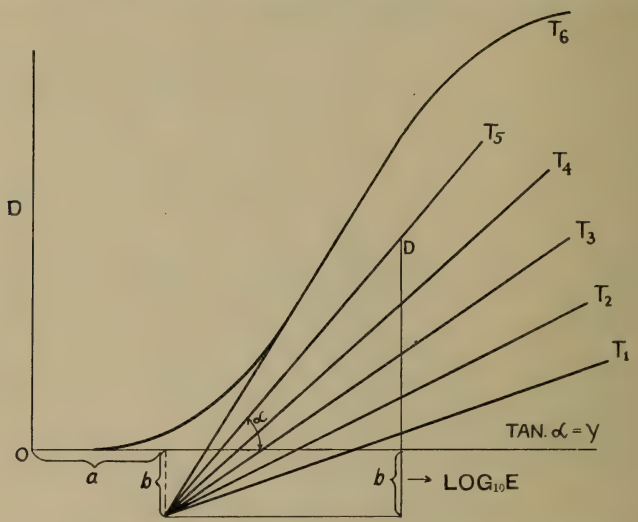


Fig. 20.—Showing Displaced Point of Concurrence of Constant γ Lines, due to Bromide in Development

certain range of bromide concentrations (which differs from one developer to another), the effect of bromide is equivalent, for the same degree of development, to a *constant depression* of density in the straight-line portion of the curve. Taking solutions containing equivalent concentrations of the reducing ions, the concentration of potassium bromide was found which was necessary to produce the same depression of density. The greater this concentration, the greater the reducing energy, or reduction-potential. This procedure has been much improved by A. Nietz, who has shown that the *depression of the intersection point* is the most reliable parameter in evaluating bromide action.

Theoretically, a functional connection can be established between

the bromide effect and reduction-potential on the following lines, which are developed more fully by the writer elsewhere.[1] The concentration of bromide will determine inversely the concentration of free silver ions, owing to the reversible reaction

$$\dot{Ag} + Br' \rightleftharpoons AgBr,$$

and the constancy of the solubility-product $[\dot{Ag}]\,[Br']$. But, from the equation for development as a reversible reaction

$$\dot{Ag} + B'' \rightleftharpoons Ag + R',$$

the lower the concentration of silver ions present, the greater must be the value of the quotient $[R'']/[R']$ at equilibrium necessary to produce a supersaturated silver solution for the same nucleation of metallic silver, that is, for the same light-exposure—otherwise expressed, the higher must be the reduction-potential of the reducer, for equivalent concentration. Hence an inverse functional relation exists between reduction-potentials and bromide concentrations producing the same downward displacement of the equilibrium point in development, defined by the common intersection point of the characteristic curves—this point being independent of the time of development.

Taking the characteristic bromide concentration producing a given depression for a selected standard developer as unity, a scale can be obtained, expressing the relative energies of developers. The following table from A. Nietz gives what are probably the most reliable results at present available:

		Relative Energy.
M/10	ferrous oxalate	0·3
M/20	*p*-phenylene diamine, hydrochloride (no alkali)	0·3
M/20	*p*-phenylene diamine, hydrochloride (alkali)	0·4
M/20	hydroquinone	1·0 (standard)
M/20	*p*-phenyl glycine	1·6
M/10	hydroxylamine..	2·0
M/20	toluhydroquinone	2·2
M/20	*p*-aminophenol (hydrochloride) ..	6·0
M/20	chlorhydroquinone	7·0
M/20	dimethyl *p*-aminophenol (sulphate) ..	10·0
M/20	monomethyl ,, ,, ..	20·0
M/20	diamidophenol..	30–40

It is necessary to note here that the higher the reduction-potential of the developer, the larger is γ_∞. There are, however, certain

[1] *Investigations on the Theory of the Photographic Process*, p. 188.

exceptions which are not at present fully understood. On the other hand, the "fogging" tendency of developers, that is, the extent they reduce unexposed silver bromide, does not stand in any necessary connection with their reduction-potential; or rather, this relation is obscured by other factors of equal or greater importance. It is also important to notice, as a practical aspect, that "fog" is proportionately more restrained by bromide than exposures.

The Time of Appearance and Factorial Development.—The primary thing in practical development, though not the only one, is to secure the right contrast, as measured by γ (gamma). Criteria are discussed later. One method of securing correct contrast, based on the principles of this section, consists simply in developing for a definite time at a constant temperature, the time for a given γ being determined from a plot of the γ, t curve for the given emulsion and developer. Another method, which also tends to eliminate guesswork, is *factorial development*, due to A. Watkins. He found experimentally that the *time of appearance* of the highlight (maximum exposure) of a negative, multiplied by a numerical factor, gives the time of development necessary to obtain a given contrast. The numerical (Watkins) factor for a specific contrast ($\gamma = 1$) is, within fairly wide limits, independent of the emulsion and of the concentration of the developer, but is characteristically different for different reducing agents. This result can be deduced from chemical kinetics. For the same velocity-function, the time required to effect a given fraction of the total reaction will stand in a constant numerical ratio to the time required to effect any other definite fraction of this decomposition. The time of appearance is, for the same observer and conditions of inspection, the time for the production of a definite small difference in density—called "difference limen". It therefore stands in constant ratio to the time for another fixed fraction of development. The great variation from one reducing agent to another, illustrated in the table, is associated with difference in reduction-potential. The low-factor developers have low energy, the high-factor developers great energy. Corresponding with this is the fact that addition of bromide lowers the Watkins factor for a given reducing agent.

Developer.	Watkins Factor.
Hydroquinone	5
p-aminophenol	16
Metol	30
Diamidophenol	60

Temperature and Development.—With all developers increase of temperature increases the rate of development, but the magnitude of the effect varies. The *temperature co-efficient* for 10° C. is the ratio of the velocity-constants of development for 10° C. difference of temperature, and some values are given in the following table:

Developer.	For 10° C.
Ferrous oxalate	1·6
Hydroquinone	2·4
Pyro-soda	1·5

With certain developers of low reduction-potential, notably hydroquinone, lowered temperature not only slows down development, but increases the induction period. Its effect is similar to that of bromide at constant temperature.

Condensed *practical inferences* from the foregoing are:

(*a*) **Secure correct exposure, i.e. within the latitude of the emulsion, if possible.**

(*b*) **Develop by time at a definite temperature, or by Watkins factor, to the contrast required—usually near unity—not by inspection and guesswork.**

(*c*) **If underexposure is unavoidable, use a high-energy developer, restrained with sufficient bromide to keep down " fog ".**

Fixation.—*The purpose of fixation is the removal of undeveloped silver halide from the plate or paper.* The silver halides are dissolved by certain substances forming complex compounds. The solubility of the silver halides in water decreases in the order AgCl, AgBr, AgI. The lower the solubility in water, the greater the complexity of the new compound formed has to be. This " complexity " is measured by the *stability constant* of the complex ion. Thus considering the solution of silver bromide in " hypo ", that is, sodium thiosulphate ($Na_2S_2O_3$), we have the following reactions:

(*a*) $2AgBr + Na_2S_2O_3 = 2NaBr + Ag_2S_2O_3$,
or, in ionic notation, $Ag + S_2O_3'' \rightleftharpoons AgS_2O_3'$.

(*b*) $Ag_2S_2O_3 + Ng_2S_2O_3 = Ag_2S_2O_3{\cdot}Na_2S_2O_3$,
or $AgS_2O_3' + S_2O_3'' \rightleftharpoons Ag(S_2O_3)_2'''$.

(*c*) $Ag_2S_2O_3{\cdot}Na_2S_2O_3 + Na_2S_2O_3 = Ag_2S_2O_3{\cdot}2Na_2S_2O_3$,
or $Ag(S_2O_3)_2''' + S_2O_3'' \rightleftharpoons Ag(S_2O_3)_3^{v}$.

With increasing concentration of thiosulphate, increasingly complex

ions are formed. The stability of the complex ion $Ag(S_2O_3)_2'''$ is measured by the quotient

$$K = \frac{[\dot{Ag}]\,[S_2O_3'']^2}{[Ag(S_2O_3)_2''']},$$

and a series of such values are given in the following table:

STABILITY OF COMPLEX SILVER IONS

Formula.	Ion.	K.
$Na_2Ag(S_2O_3)_2$	$Ag(S_2O_3)_2''$	$0{\cdot}98 \times 10^{13}$
$Na_4Ag(S_2O_3)_3$	$Ag(S_2O_3)_3$	$3{\cdot}45 \times 10^{13}$
$NaAg(CN)_2$	$Ag(CN)_2'$	$0{\cdot}11 \times 10^{22}$
$NaAg(CNS)_2$	$Ag(CNS)_2''$	$0{\cdot}6 \times 10^{9}$
$Ag(NH_3)_2Br$	$Ag(NH_3)_2^{\cdot\cdot}$	$1{\cdot}3 \times 10^{8}$

It will be seen from this table that the silver cyanide ion is the most stable, which corresponds with its use in fixing plates made with silver iodide, the least soluble halide. At the same time these figures emphasize the desirability of using ample excess of fixing salt, and not carrying the bath too near the saturation limit.[1]

The Rate of Fixation.—The speed of fixation is mainly determined by diffusion of thiosulphate (hypo) into the film and of dissolved silver halide out of the film. This is well shown by fixing plates in one case suspended face down, in the other face up, without stirring or rocking. The face-down plates will be fixed in approximately half the time required for the face-up plates. For concentrations up to 10 per cent the rate of fixation is nearly proportional to the concentration of thiosulphate, and is greatly accelerated by stirring or rocking. In practice higher concentrations are used—up to 30 per cent—and it has been shown that the *time of fixation* diminishes with increased concentration up to 40 per cent, after which it again increases. The existence of this minimum time of fixation is due to the fact that, by increasing the concentration of the salt, the swelling of the gelatine is reduced. Acceleration of fixation is produced by adding to the bath *substances such as ammonia or sulphocyanide which increase the swelling of the gelatine*, but care must be taken that the gelatine is not excessively softened.

[1] The actual limit is fixed by the tendency to form silver sulphide, which may be tested by exposing a piece of soaked paper to air and light. If it darkens, the bath is unsafe.

The Acid Fixing Bath.—Acid fixing baths were introduced by Lainer in 1889 with the object of bringing in the advantages of the acid clearing bath frequently used after alkaline development *to reduce stain.* If mineral acids are added to thiosulphate solution, sulphur is rapidly precipitated. With organic acids this occurs less rapidly, but will still happen. Lainer found that the previous addition of sodium sulphite to the thiosulphate solution allowed considerable acid to be added without decomposing the thiosulphate. This protective action of the sulphite is probably due to its being a reaction product of the reversible equilibrium

$$\underset{\text{thiosulphate anion}}{S_2O_3''} + \underset{\text{hydrogen ion}}{\dot{H}} \rightleftharpoons \underset{\text{bisulphite ion}}{HSO_3'} + \underset{\text{sulphur}}{S}.$$

Hardening Solutions.—In many cases, particularly where the negative is likely to be subjected to after-treatment, such as bleaching or intensification, or in hot weather, it is desirable to harden the gelatine film. Temporary hardening, e.g. during development, may be effected by adding considerable amounts of neutral salts, such as sodium sulphate (Na_2SO_4), which greatly repress the swelling of the gelatine. The same result is effected by using high concentrations of sulphite and carbonate in the developer, or using, as alkali, considerable trisodium phosphate. This action is only temporary, and the gelatine again swells when the salt is washed away and the film transferred to water. Permanent hardening, or tanning, as already mentioned, can be effected by solutions of formaldehyde (formalin), used from 1 to 5 per cent, or of potassium or chrome alum. Hardening with alums depends upon the hydrolysis of the alum and combination of the hydrous oxide, or possibly a hydrous basic salt, with the gelatine. It is therefore reduced by excess acid; on the other hand, sufficient acidity must be present to prevent excessive hydrolysis of the alum in the absence of gelatine. Attempts to combine the alum hardener with the acid fixing solution are limited by these conditions. If the acidity is too high, sulphur is precipitated; if too low, alumina. The use of certain organic acids, e.g. citric acid, permits considerable amounts of alum to be present in a fixing solution of lower acidity than is compatible with repression of hydrolysis of the aluminium sulphate. The reason for the stability in these cases is the tendency of the organic acids—particularly polybasic and hydroxy acids—to form stable complex molecules with aluminium. On the other hand, this property greatly

reduces the hardening action of the alum, hence little is gained, and it is best to use a separate hardening bath where satisfactory alum hardening is desired.

Reduction, Bleaching, and Intensification.—These operations are grouped together, not only from their affinity in photographic practice, but because *bleaching*, in the sense of converting the silver image into a reactive but insoluble (in water) compound,

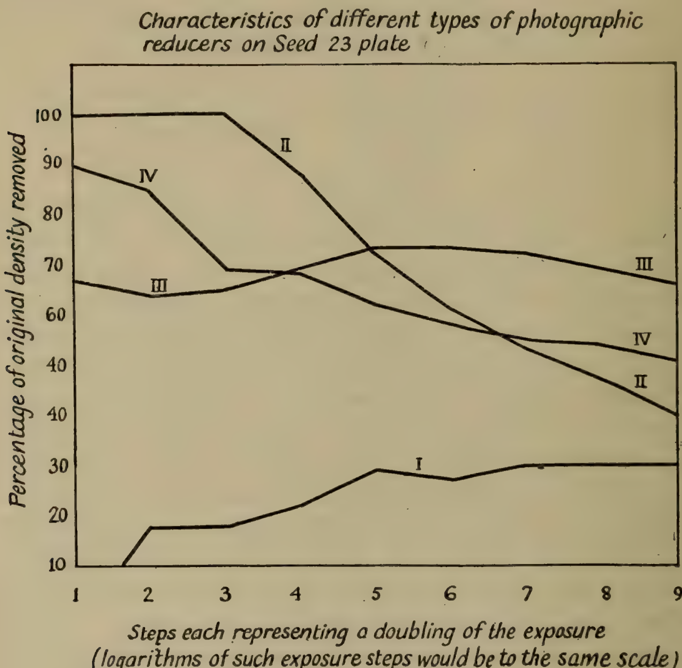


Fig. 21.—(From Nietz and Huse)

I, Ammonium persulphate. II, Farmer's reducer. III, Permanganate plus persulphate. IV, Permanganate.

usually white, is frequently the opening move in both reduction and intensification.

Photographic *reduction* is a confusing misnomer, since chemically the operation is an oxidation, consisting essentially in the reversal of the step effected in development, that is, the silver image is, partially, reconverted from the metallic to the ionic condition:

$$Ag \text{ (metal)} \rightarrow \dot{Ag} \text{ (ion)}.$$

Since few silver salts are sufficiently soluble in water to allow silver

to be removed by simple salt formation, with most reducers the operation is effected in steps:

$$\text{Ag (metal)} \rightarrow \dot{\text{Ag}} \text{ (ion)} \rightarrow \text{AgX (insoluble)}$$
$$\rightarrow \text{(AgZ)X (soluble complex)},$$

that is, the insoluble silver compound is " fixed " out, so that the operation is a combination of oxidation (bleaching) and complex solution (fixation). Sometimes these operations are combined, at others effected in succession.

Reducers must not attack gelatine or dissolve silver with uncontrollable rapidity. This condition eliminates the direct use of nitric acid. Again, it is desirable that they do not stain or tan gelatine excessively, nor change the colour of the image too much. The following table is intended to give a bird's eye view of the principal combinations, noting the form in which the silver is actually removed in solution.

Some Typical Reducers

Reducer.	Chemical Composition.	Silver removed as:	Introduced by:
Ferric sulphate	$Fe_2(SO_4)_3 + H_2SO_4$	Ag_2SO_4	—
Potassium permanganate (acid)	$KMnO_4 + H_2SO_4$	Ag_2SO_4	Namias.
Quinone (acid)	$C_6H_4O_2 + H_2SO_4$	Ag_2SO_4	Lumière.
Ceric sulphate	$Ce(SO_4)_2$	Ag_2SO_4	Lumière.
Ammonium persulphate	$(NH_4)_2S_2O_8$	Ag_2SO_4	Lumière.
Ferric oxalate and potassium bromide, followed by " hypo "	$Fe_2(C_2O_4)_3 + KBr$ $(+ Na_2S_2O_3)$	$Na_4Ag_2(S_2O_3)_3$	Belitzki.
Farmer's reducer:— Potassium ferricyanide plus " hypo " ..	$K_6Fe_2Cy_{12} + Na_2S_2O_3$	$Na_4Ag_2(S_2O_3)_3$	H. Farmer.

Reducers have been classed (by R. Luther) as:

Superproportional, i.e. those removing a greater percentage of silver from the higher than from the lower densities, e.g. ammonium persulphate (under certain conditions).

Proportional, i.e. giving the same percentage reduction of all densities, e.g. a mixture of potassium permanganate and ammonium persulphate.

Subproportional, i.e. removing a greater percentage from the low densities than from the higher ones, e.g. potassium permanganate; still more, Farmer's reducer (fig. 21).

Intensification.—The objects of intensification are just the opposite of those of reduction, namely, to increase density and contrast. Generally this is for underdeveloped negatives, since little can be done for underexposed ones. A useful classification of negatives from this standpoint, and an excellent practical survey of intensification and reduction, is given by H. W. Bennett. Attention may also be directed at this point to the difference in regard to intensification between collodion and gelatine plates. Many intensifiers, with due modifications, are suitable for either, but the fact remains that in advancing from wet collodion to gelatine emulsions there is an increasing complexity in the reaction conditions.

Whilst the conditions with wet collodion readily permit and even invite after-treatment, such as intensification, gelatine offers greater difficulties, owing to greater absorption and retention by gelatine, the tendency of gelatine to soften or reticulate, and the greater complexity of structure of the image in gelatine. *Great care in fixing and washing is necessary if intensification is to be successful.* The methods used depend upon (*a*) the deposition of silver from a physical developer, (*b*) the " bleaching " of the silver image to a halide, or a ferrocyanide, generally followed by redevelopment or conversion to sulphide. The following table gives examples and indications of the reactions involved.

INTENSIFICATION REACTIONS

Bleaching Solution.	Primary Product.	Blackening Solution.	End Product.
Mercuric chloride[1] ($HgCl_2$)	Silver mercury chloride ($AgCl:Hg_2Cl_2$)	Ammonia	Complex silver mercur - ammonium chlorides
,,	,,	Sodium sulphite (Na_2SO_3)	$Hg(SO_3)_2Hg_3 + Ag$ (Some Hg and half silver are dissolved out)
,,	,,	Ferrous oxalate	Ag:Hg (metal)
,,	,,	Alkaline developers	Ag:Hg (metal) (Some Ag dissolved out by sulphite)
Lead ferricyanide	Silver and lead ferrocyanide	Sodium sulphide	Lead sulphide and silver sulphide
Potassium bichromate hydrochloric acid	Silver chloride and chromium chromate	Amidol	Silver and chromium chromate

[1] The bromide or iodide may equally well be used.

Space forbids us to discuss fully the more detailed aspects of the chemical reactions involved, but a word must be said as to the relative physical and photographic intensifications effected. If the densities, measured photometrically, of a strip negative are plotted before and after intensification, we may obtain a result similar to that shown in the figure (fig. 22), which shows results of A. H. Nietz and K. Huse with a number of intensifiers. An intensifier will be *photometrically proportionate* if the ratio of densities before and after is constant. Frequently, however, the lowest densities actually lose somewhat, owing to solvent action of the blackening solutions used. A negative, however, is actually used to print through on to a positive material, which will not have the same colour-sensitiveness as the eye. Consequently, the ratio of intensification determined photometrically will not necessarily give the effective photographic intensification; in fact, it will be generally different, since most intensification processes alter the colour of the deposit. The photographic effect may be determined by finding the exposure necessary to give a certain density on a given printing material through the intensified negative, and comparing this with the exposure necessary to give the same density through the unintensified negative. Doing this step by step, and taking $\log_{10} E_1/E_2$ as the photographic density D_p, the *printing density* curve can be compared with the visual (or photometric) density curve. The ratio of the photographic development-factor[1] to the photometric development-factor determined thus has been termed the *colour co-efficient* of the negative.

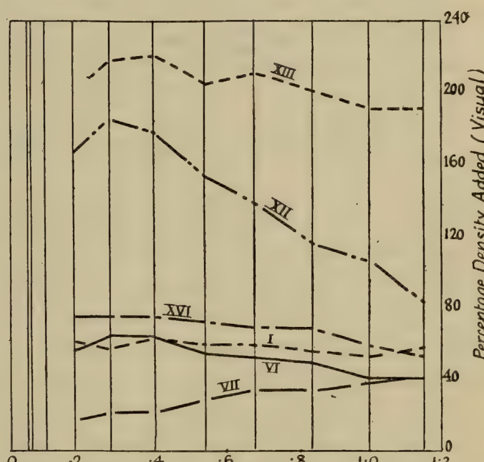


Fig. 22.—Characteristics of Different Intensifiers (Nietz and Huse)

[1] See p. 145.

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SECTION IV.—THE PHYSICAL CHEMISTRY OF POSITIVE PROCESSES

Developing-out Emulsion with Silver Salts.—Although historically printing-out processes preceded developing processes for positive work, the latter are becoming much the more generally used and important, and the discussion of them follows naturally upon the treatment of negative-making. The chemistry of the preparation and use of silver halide positive emulsions does not differ essentially from that of negative materials. The principal differences arise from differences of technical requirements and from the increased predominance of *silver chloride* as the sensitive halide. The technical requirements are, roughly, lower sensitiveness, greater fineness of grain of the silver deposit, and flexibility and control of the tone of the image. Positive materials for development may be classified as follows:

MATERIALS USED IN POSITIVE EMULSIONS

Name and Purpose.	Sensitive Material.	Sensitiveness.
Cine. positive. Bromide, lantern. ,, enlargement.	Silver bromide or bromo-iodide.	1/10 to 1/30 1/30 ,, 1/50 1/50 ,, 1/100
Gas-light papers. Lantern work.	Silver chlorobromide and silver chloride.	1/100 ,, 1/500

The " sensitiveness " figures are somewhat arbitrary average

figures for white light, and are relative to slow negative emulsions. In proportion as silver chloride is used, the spectral sensitiveness shifts back into the violet and ultra-violet. It is for this reason that the so-called "gas-light" papers, made from silver chlorobromide and chloride, can be exposed some time with impunity to light which is weak in the short wave-lengths, such as gas-flames. In regard to their preparation, the only points we need to notice are, firstly, the relatively lower concentration of the reactants used in making the emulsion, which results in lower dispersity (finer grain) and less silver per unit area; and secondly, the smaller part played by the ripening processes. Thus the amount of silver per unit area in bromide papers for rotary photographic production is of the order 0·018 gm. Ag per 100 sq. cm., whilst with negative emulsions it is of the order 0·10 gm. Ag per 100 sq. cm.

Development of Positive Emulsions.—No essentially new physical or chemical principles distinguish the development of positive emulsions from that of negative ones, but certain factors of relatively small importance in negative development assume a large rôle, and conversely. This change may be expressed by saying that the factors of diffusion and absorption become much less important than the chemical aspects of development; whilst the type of development approaches what has been termed "physical" development, that is, it involves the reduction of silver from a solution which interacts with the developer. This tendency toward physical development is not due to the actual use of an auxiliary silver solution, but to the solvent action of sodium sulphite upon fine-grained silver bromide and on silver chloride.

In general, developers for positive emulsions, and particularly for silver chloride, must have their reducing energy less than for negative emulsions. This is secured by diluting, and lowering the amount of alkali. The distinction between *normal* and *retarded* development which was made for negative emulsions holds also for positive emulsions, with this difference, that the normal development of positive emulsions already corresponds to what would be moderately retarded development for negative emulsions, whilst retarded development of positive emulsions is carried to a point giving special warm-toned, very fine-grained images. Coming now to the measurement of the progress of exposure and development with developing-out *papers*, we may note at once that here it is not the mass of reduced silver which is of chief importance, but the *relative reflecting power* of it.

The *reflection-density* is the name given to the following expression: if we measure the intensity of light reflected from the paper base, free from image, and call this i, and term the intensity reflected from any field of the image (after exposure, development, and fixation) i', then the reflection-density is $\log_{10}\frac{i}{i'}$. Putting $i = 1$, the *relative reflection-density* D_r is $\log_{10}1/R$, where R is the reflecting-power. To eliminate regular reflection, the reflecting-power is measured with illumination at 45° to the plane of the paper. It was shown by Kieser that under these con-

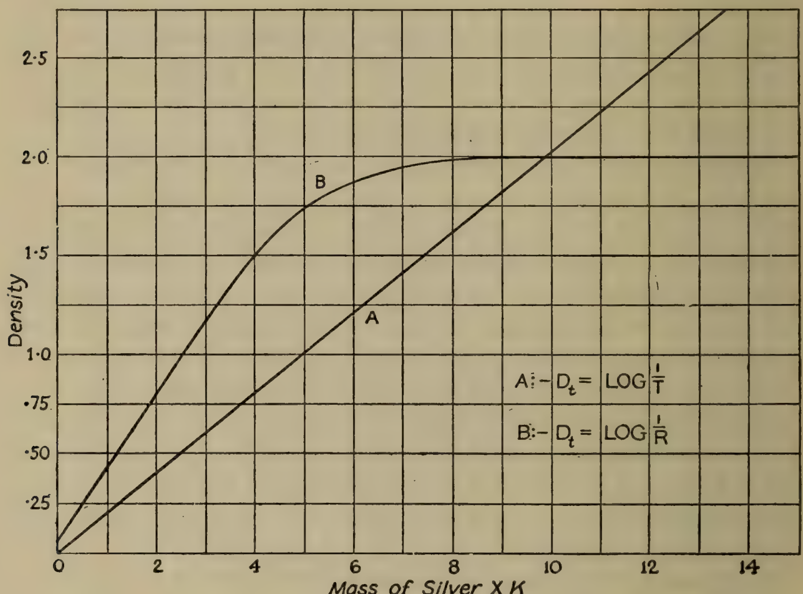

Fig. 23.—Showing Effect of Silver deposited on Reflection- and Transmission-density of Positive Emulsions

ditions papers give a characteristic ***maximum black***, i.e. a maximum value for D on increase of exposure. This value is reduced, for the same emulsion, by " matting " the surface, e.g. by including starch and similar diffusing substances in the emulsion. Renwick later compared the reflection-density D_r and the transmission-density D_t (= $\log_{10}1/T$)* for the same series of deposits. He showed that D_r does not increase proportionately with D_t, but reaches a maximum independent of D_t, which continues to increase with the mass of the deposit (fig. 23). The influence of time of development upon the characteristic curves for papers, obtained by plotting D_r as ordinate against $\log_{10}E$, was systematically studied by

* Where T is the transparency.

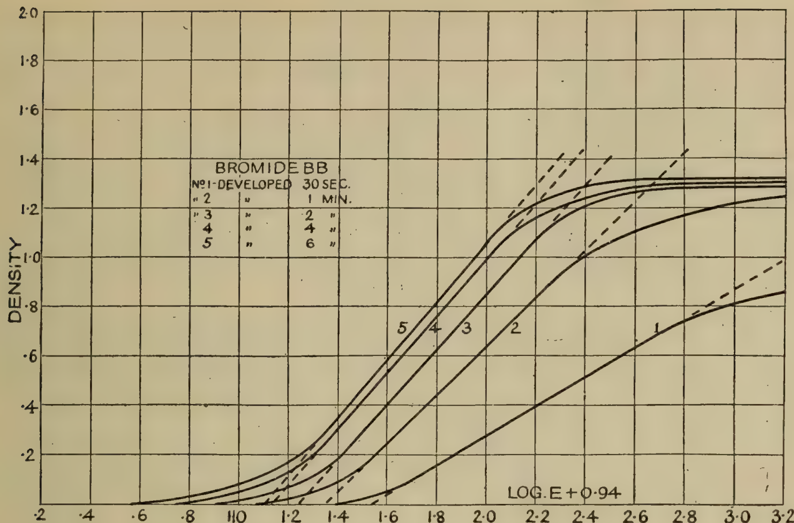

Fig. 24.—Characteristic Curves for Bromide Papers

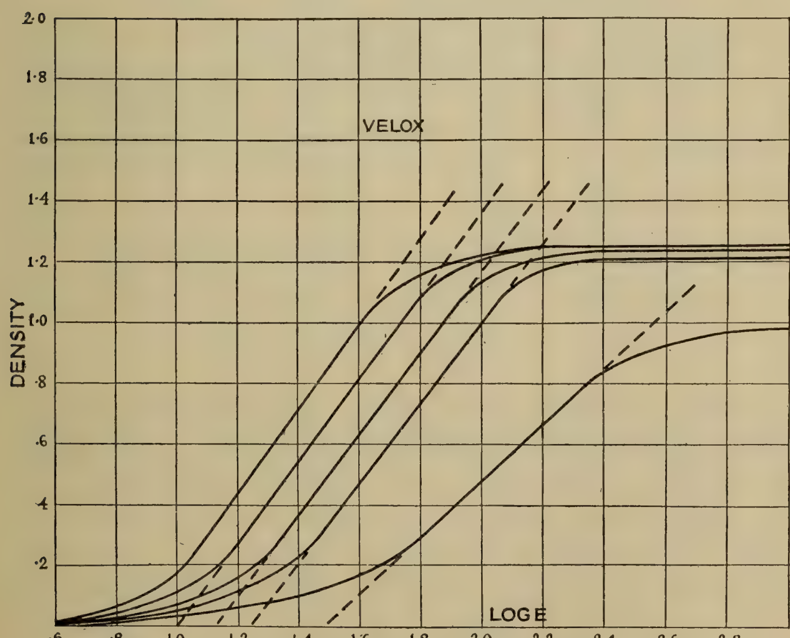

Fig. 25.—Characteristic Curves for Velox Papers

Nutting, Jones, and Mees. With *bromide paper* they found a pronounced regression of the inertia, i.e. a displacement of the characteristic curve as shown in fig. 24, which is typical of retarded development with negative emulsions (see p. 46).

At first the value of γ, the slope of the straight-line portion (or the tangent to the point of inflexion, in the case of curves showing no straight-line portion) increases simultaneously with the regression of the inertia, that is, the shift of the point of intersection of the straight line with the $\log_{10}E$-axis. After the value of γ has reached a limit, the regression of inertia may continue to go on, without change of γ, or increase of the maximum black.

With the more rapidly developing chloride (gas-light) papers, the effect of increase in time of development is practically limited to a regression of the inertia, without change in γ, except in the very earliest stages, where the curves are usually of distorted form (fig. 25).

The following "constants" may be derived from the sensitometric curves of sensitive materials on paper, and regarded as tentative expression of their characteristics:

Constant.	Symbol.	Significance.
(*a*) Maximum (reflection density)	D_{max}.	Highest attainable density.
(*b*) Contrast element ..	$\frac{dD}{d \log_e I}$	Differential.
(*c*) Gamma	γ	Value of (*b*) for straight-line portion, or at inflexion-point.
(*d*) Latitude	L	Range of intensities reproduced on straight-line portion.
(*e*) Rendering power	R	$\frac{10L}{S}$.
(*f*) Total scale	S	Range of intensities reproducible by density differences.
(*g*) Standard exposure	E_s	The exposure in C.M.S.[1] necessary to print through a negative density of 2·0.[1]

Colour Variations of the Image with Retarded Development.—If considerable over-exposure be given to developing-out papers or lantern plates, and a strongly restrained developer used, images can be obtained varying in tone from greenish-black to chalk-red.

These colour variations are primarily due to alteration of the dispersity of the deposit. It can be shown that if colloidal gold

[1] The "candle" is defined as one visual candle-power from a tungsten lamp at a rating of 1·25 watts per m.h.cp. (mean horizontal candle-power).

or silver sols are prepared, and differing amounts of a previously prepared "nucleus" solution added to each before the reducer is added to the metal salt, that differently coloured colloid metal sols are obtained. Innoculation in this case is exactly parallel with exposure to light, and increase in the amount of innoculating sol corresponds to increase in the number of nuclei. This same result is effected by increase in exposure to light. The greater the number of nuclei, the smaller each particle of silver formed, since only the same total amount of silver is present available for reduction. Although the toned images producible in this way have not much value for practical work, the rationale of their production is of great theoretical significance in appreciating the relation of photography to colloid chemistry.

Toning Processes for Developing-out Papers and Transparencies.—The most important practical processes for changing the colour of the developed image are the *sulphide* and the *ferrocyanide* processes, or rather groups of processes. In the first of these the silver image is converted to silver sulphide,

$$Ag \rightarrow Ag_2S \text{ (sepia and brown tones).}$$

This may be accomplished directly in a single bath as in the process with alum and thiosulphate. In this process nascent sulphur is released by the action of acid derived from the hydrolysis, by warming, of the aluminium sulphate upon thiosulphate. The reactions may be represented as:

$$\begin{aligned} Al_2(SO_4)_3 + 3Na_2S_2O_3 &= Al_2(S_2O_3)_3 + 3Na_2SO_4, \\ Al_2(S_2O_3)_3 + 3H_2O &= Al_2(OH)_3 + 3SO_2 + 3S; \\ \text{or} \quad Al_2(SO_4)_3 + 3H_2O &= Al_2(OH)_3 + 3H_2SO_4, \\ Na_2S_2O_3 + H_2SO_4 &= Na_2SO_3 + SO_2 + S, \\ \text{and} \quad Ag_2 + S &= Ag_2S, \end{aligned}$$

although it is probable that intermediate reactions of a more complicated type occur, which involve the formation of polythionates. The indirect methods of sulphide toning depend upon the preliminary conversion of the silver to silver halide, e.g. bromide, or to silver ferrocyanide, followed by conversion of these to silver sulphide by interacting with a soluble sulphide.

$$\begin{aligned} Ag + Br &= AgBr, \\ 2AgBr + Na_2S &= Ag_2S + 2NaBr. \end{aligned}$$

Recently processes using *selenium* and *tellurium*, either alone or in conjunction with sulphur, have been developed.

Toning with Ferricyanide.—Processes depending upon the reactions of the silver image with soluble ferricyanides, giving insoluble ferrocyanides of various metals, afford a variety of tones. These processes may be grouped as follows:

$$\text{Direct}\left\{\begin{array}{lll}\text{Uranium} & \rightarrow & \text{red-brown.}\\ \text{Copper} & \rightarrow & \text{red-brown.}\\ \text{Iron} & \rightarrow & \text{blue.}\end{array}\right.$$

$$\text{Indirect}\left\{\begin{array}{l}\text{Lead ferrocyanide}\\ \text{Silver ferrocyanide}\end{array}\right\} \rightarrow \left\{\begin{array}{l}\text{Uranium ferrocyanide.}\\ \text{Copper.}\\ \text{Iron.}\\ \text{(Cobalt).}\\ \text{(Manganese).}\end{array}\right.$$

The formation of silver ferrocyanide proceeds, as a whole, accord- to the equation

$$2Ag_2 + 4K3FeCy_6 = Ag_4FeCy_6 + 3K_4FeCy_6.$$

If in place of potassium ferricyanide a soluble ferricyanide of a heavy metal yielding a coloured ferrocyanide be used, or if conversion to silver ferrocyanide be followed by treatment with a soluble salt of a toning element (e.g. uranyl nitrate), coloured ferrocyanides are formed. To regulate the reaction, and in particular to prevent staining the gelatine, it is necessary to have a certain amount of an organic acid or acid salt, such as citric or tartaric acid, present. These acids form complex molecules with the heavy metal compounds (e.g. copper in presence of tartrates, &c., is not precipitated by alkali); their restraining action may be regulated by adjustment of the acidity, i.e. the H-ion concentration. A further function, identical with that already discussed in connection with hardening of gelatine, is to prevent coagulation of the gelatine.

In this connection a process of replacing the silver image by a dye image, due to J. Traube, may be mentioned. The silver image is converted, by a bleach of ferricyanide and potassium iodide, into silver iodide. This substance strongly absorbs basic dyes. The dyed image is then treated with a strong thiosulphate solution, to dissolve out the silver iodide, and a mordant fixing the dye in the gelatine. In recent processes, silver ferrocyanide has been used in place of iodide. The process is valuable in colour photography.

Silver Printing-out Processes.—With the advent of developing-out papers, direct silver printing processes are tending to become of more historical than practical importance. The basis of these papers is silver chloride, together with an excess of a silver salt, which is suspended in either albumen, collodion, or gelatine. The silver chloride is very finely divided, the largest particles being just visible microscopically. Silver nitrate may be used as the excess soluble silver salt, but it is more usual to employ a silver salt of an organic acid, such as silver lactate, oxalate, tartrate, or most generally citrate. The function of this ingredient is to act as a chemical sensitizer by absorbing chlorine given up by the silver chloride which has been acted upon by light.[1] The tone of the primary image—on printing—is determined by the size of the particle of silver produced. This, in turn, is affected not only by the emulsifying conditions and formula used, but by the conditions of exposure, particularly of *intensity of light* and of *humidity*.

The colour range of colloid silver with increasing size of particle is as follows:

$$\text{yellow} \rightarrow \text{red} \rightarrow \text{lilac} \rightarrow \text{blue}.$$

The influence of the intensity of the light used in printing, and of the humidity on the direct printing (proof-tone) tone is given in the following synopsis:

Light Intensity.	Humidity.		
	High.	Normal.	Low.
Strong.	Light red, soft.	Deeper red.	Normal purple.
Moderate.	Deeper red.	Normal purple.	Bluer and hard.
Weak.	Normal purple.	Bluer and harder.	Very blue and hard.

The tones obtained on printing are altered on fixation of the unchanged silver salts, so that to obtain pleasing images resort is had to toning with gold or platinum or palladium or superposition of these, when silver is replaced by the nobler metals

$$2NaAuCl_4 + 3Ag_2 = Au_2 + 2NaCl + 6AgCl.$$

The use of separate toning and fixing baths has been largely superseded by combined baths. The chemistry of their operation,

[1] F. Weigert has recently suggested that it supplies all the silver to intensify nuclei.

though interesting, is not of sufficient importance to delay us here. A still further practical simplification of procedure is effected in the use of various self-toning papers, which contain the gold salt in the emulsion (usually made with collodion), and only need immersion in the fixing bath to complete the toning process.

Ferroprussiate and Platinotype Processes.—The foundation of both these processes is the reduction of ferric to ferrous salts by light. In the ferroprussiate process, used so extensively for " blue prints ", paper is salted with a double *ferric ammonium citrate.*

This substance is prepared by dissolving hydrous ferric oxide in citric acid, and adding to the solution an equivalent amount of ammonium citrate. On exposure to light the ferrous salt is produced, and the image developed with a solution of potassium ferricyanide, giving *Turnbull's blue,*

$$3FeCl_2 + Fe_2(CN)_{12}K_6 = Fe_2(CN)_{12}Fe_3 + 6KCl.$$

More generally, the ferricyanide of potassium solution and the ammonio-citrate of iron are mixed and the paper sensitized with both, so that the blue image is formed directly in light. The prints are fixed by washing in slightly acidified water. So-called positive blue prints (Herschell-Pellet process) are made by developing the image with potassium ferrocyanide. This gives Prussian blue with the unchanged ferric salt, and colourless ferrous ferrocyanide on the exposed parts, which is removed, giving white lines.

The platinotype process depends upon the reduction of ferric to ferrous oxalate by light:

$$Fe_2(C_2O_4)_3 = 2Fe(C_2O_4) + 2CO_2.$$

The ferrous oxalate is dissolved as a double salt in potassium oxalate. It reduces a platinum salt, with which the ferric oxalate is mixed before sensitizing, to metallic platinum.

A *platinous* salt is used, usually potassium chloro-platinite, the double combination of platinous chloride and potassium chloride. The reduction may be represented by the equation

$$6FeC_2O_4 + 3K_2PtCl_4 = 2Fe_2(C_2O_4)_3 + Fe_2Cl_6 + 6KCl + 3Pt.$$

Development is effected by treating the paper with a solution of potassium oxalate, which dissolves the ferrous oxalate and brings it into reaction with the platinous salt. As with ferroprussiate paper, a modification allowing simultaneous development on exposure has

been made by incorporating the developing substance in the paper. Platinotype papers must be kept in a very dry atmosphere, kept dry by calcium chloride, before use, if they are not to spoil. The process gives very beautiful and permanent results, but has been adversely affected by the increased shortage of platinum. The total scale is very great, but the latitude and the maximum blacks are relatively low.

Processes with Bichromated Colloids.—The action of light on colloids impregnated with soluble bichromates, in particular on gelatine and glue, is second only to that on silver compounds in photographic importance. *The fundamental result of the photochemical reaction is the formation of a compound of chromium oxides with the gelatine which resists water, its swelling in the cold being diminished in proportion to the action of light, and its dissolution in warm or hot water being prevented.* The carbon printing process depends upon the rendering of a pigment containing gelatine insoluble, by sensitizing it with bichromate. Various photomechanical processes make use either of this effect or of the change in swelling. (See "Photography applied to Printing", Ch. XII.) The possibility of making bichromated glue (gelatose) insoluble is the keynote of the "half-tone" process. In this process, the original image is broken up optically into dots, the number of dots per unit area being proportional to the intensity of the original image. The dots are printed in bichromated glue, spread in a thin layer on a copper or brass plate, and the residual unexposed soluble glue washed off with water. The plate is then baked to harden the dot-images, and is then etched in a solution of ferric chloride, which attacks and dissolves the metal where not protected by the resistant.

The chemistry of bichromate processes is not yet completely clear. Investigations by J. M. Eder, Lumière, Seyewetz, and others indicate that the course of the reaction consists in a reduction of the bichromate, or of chromic acid, to chromium sesquioxide, Cr_2O_3, some of which then reacts with excess bichromate, or chromic acid, to form a chromium *chromate*, which is regarded as actually responsible for the tanning[1] of the colloid. These reactions may be represented as follows:

$$2H_6CrO_6 \xrightarrow[\text{Light.}]{} Cr_2O_3 + 6H_2O + 3O,$$

$$Cr_2O_3 + CrO_3 = \underset{\text{Chromium chromate.}}{Cr_2CrO_6} = (3CrO_2).$$

[1] I.e. the rendering of the colloid insoluble.

The composition of the oxides of chromium which tan gelatine in this process is not definite, however, and their identity with the unstable chromium chromate can hardly be regarded as proved. Further, the existence of the latter substance is somewhat questionable. In any case, the following facts are important. The neutral chromates, with the exception of ammonium chromate, do not sensitize gelatine. The reason for this exception is simple. The fundamental substance reacting to light is either the chromic acid anion, Cr_2O_7'', or the chromium trioxide, which forms part of it, according to the equilibrium

$$Cr_2O_7'' \rightleftharpoons CrO_4'' + CrO_3.$$

Ammonium chromate solution, when evaporated, loses ammonia, forming ammonium bichromate, so that the exception is only apparent:

$$2(NH_4)_2CrO_4 = (NH_4)_2Cr_2O_7 + 2NH_3 + H_2O.$$

In general, neutral chromates are converted to bichromates by acid, whilst, conversely, bichromates are restored to chromates by alkali. There does not appear to be much difference in the sensitizing power of the bichromates of potassium, sodium, lithium, and ammonia, provided the acidity is the same in each sensitizing bath. It was found by Abney that the tanning action of light continued after a relatively short preliminary exposure. This points to the initial formation of a photocatalyst, which then further reacts with excess bichromate and gelatine to form the tanned image.

References (Section IV).

F. F. Renwick, *The Photographic Journal*, **53**, 127 (1913).

L. A. Jones, P. G. Nutting, and C. E. K. Mees, *The Photographic Journal*, **54**, 342 (1914).

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Photographische Chemie und Photochemie, Part I, by A. Lainer (R. Lechner, Vienna, 1899).

Section V.—Sensitometry and the Reproduction of Tone Values

By *sensitometry* was originally implied only the determination of the light-sensitiveness of a material. The sensitiveness was defined as the least amount of light just producing a visible impression under

specified conditions. To determine it, the material was exposed behind a graded scale of opaque screens to a constant source of light. In the Warnercke sensitometer, which played a valuable part in the early development of the gelatino-bromide dry plate, the opacity or intensity scale consisted of a piece of glass covered with a series of squares of pigmented gelatine, each square having a quite opaque number printed on it, and each letting through one-third of the light of the preceding one. A fairly constant and uniformly distributed light was secured by a phosphorescent tablet. This had to be " activated " by exposure to an inch of burning magnesium wire and used one minute after. The modern radio-luminous materials would be more satisfactory. A more reproducible sensitometer of this type, but using a standard light-source, is the Chapman Jones plate tester.

Sensitometers of this type have been and are still of great value for preliminary work. It was evident, however, at a relatively early period that they did not give sufficient information as to the quantitative relations between the growth of the image with exposure, and the capacity of negative and positive emulsions for rendering different ranges of contrast in a subject. Also, the numerical " sensitiveness " values they give are inadequate, being based on the beginnings of visibility in the image and ignoring the further strengthening of it. The quantitative investigation of the action of light on negative and positive materials was initiated by Sir W. de W. Abney. He introduced photometric methods for determining the effect of light in relation to exposure, measuring the *transparency* of negative images, and the *reflecting power* of positive images, plotting these against the exposures on a logarithmic scale.

In 1890 F. Hurter and V. C. Driffield introduced the conception of the *density* of the photographic deposit, already defined (see p. 144) as:

$$\begin{aligned} D &= \log_{10}(\text{opacity}) = \log_{10}(I_o/I) \\ &= -\log_{10}(\text{transparency}) = \log_{10}(I/I_o), \end{aligned}$$

where I is the intensity transmitted, and I_o the incident intensity.

Within certain limits the density is proportional to the mass of silver per unit area. Their method of plotting the characteristic curve has also been noticed (p. 145), and such " H. and D." or characteristic curves have since been generally used in the study of photographic fundamentals. The term " sensitometry " has now come to mean the accurate quantitative determination of the photographic

properties of negative and positive materials. Before considering some of the results of this enquiry, a brief description of sensitometric apparatus is desirable.

Sensitometric Apparatus and Methods.—In general, a complete sensitometric equipment requires:

(*a*) A reproducible light-source of constant intensity.
(*b*) Definition and determination of the spectral quality of the light.
(*c*) An exposure instrument for producing an accurate and extended scale of exposures.
(*d*) A photometer for measuring densities, &c.

Considering these in order, we may note:

(*a*) Various primary and secondary standard light-sources have been used. Hurter and Driffield used the parliamentary candle, which is far from satisfactory, J. M. Eder a small benzene lamp, standardized on the Hefner amyl acetate primary standard. Sheppard and Mees used acetylene gas, burning under constant pressure and fed to a special screened burner. With recent improvements this has been found to make a very satisfactory source. Electric glow-lamps, as used for standards in photometry, may be employed, but require careful control. The intensity varies very rapidly with the electrical pressure, hence they are best run off an accumulator. The quality or spectral energy-distribution depends upon the temperature of the filament, which again depends upon energy consumption.

(*b*) Since photographic sensitiveness varies greatly with the wavelength of the light used, it is very necessary that this be properly defined and controlled. Although daylight has not an invariable spectral composition, there are some advantages in reducing acetylene or tungsten light to an artificial " daylight standard " by compensating absorption screens. In the specific application of sensitometry to orthochromatic and colour photography, this daylight may be divided into two or three broad spectral regions by suitable absorption screens or filters. Finally, for the precise determination of the influence of wave-length on gradation and speed, the light must be spectrally resolved, by the aid of some type of spectroscopic monochromator.

(*c*) It is in respect of the actual exposure scale that we find perhaps the widest variation in apparatus and procedure. As a

photometric magnitude, exposure is defined as the product of the intensity of the light into the time of exposure, thus:

$$E = it,$$

where E is the exposure, i the intensity of light, and t the time of exposure.

The intensity of light at any point is measured by the radiant energy, transmitted in unit time, across a unit area at right angles to the direction in which the light is shining. Bunsen and Roscoe concluded from their classic work on the union of hydrogen and chlorine in light, and from their actinometric experiments with silver chloride printing-out paper, that *the photochemical effect was always the same for the same total amount of incident energy*. If light is crossing a normal area A in a field of uniform intensity of light, the energy transmitted across the area is measured by Ait, and this energy determines the photochemical effect. If the area in question is constant, the photochemical effect is determined by it, i.e. by E, the technical *exposure*. This law was found by Abney to break down when applied to gelatine emulsions with development. As the intensity is diminished below a certain value, a more than proportional increase of the time is necessary to secure the same density, in fact the photochemical effect is not strictly constant for constant E. We shall return to this specifically later, but may note at once that it is therefore by no means unimportant whether the exposure scale used in a sensitometer is a *time scale* or an *intensity scale*. As the latter scale was historically earlier we shall refer to it first. *Intensity scales* composed of increasing layers of paper are not satisfactory for any but rough work, owing to complicated internal reflection of light and the poor prospects of accurate reproduction. Pigment scales, in gelatine, are much better, but, as noted later, are difficult to produce in a completely non-selective form (neutral tint). They may be either stepped or in continuous wedge form (see p. 120). Another type

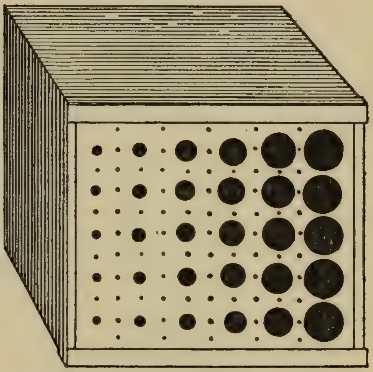

Fig. 26.—Tube-sensitometers for Testing Plates and Papers

of stepped intensity-scale is the so-called *tube-sensitometer* (fig. 26). This consists of a series of internally blackened tubes, closed at one end by a series of small apertures increasing from tube to tube in area in known ratio, e.g. $1 : \sqrt{2}$. These are all uniformly illuminated and give exposures at the other end in the ratio of the apertures.

Time scales may be divided fundamentally into continuous and intermittent, according as the exposure for any step is made continuously or by discontinuous increments.

The amount of radiant energy passed to the sensitive material for any given step of the two scales may be the same, but the photographic effect is different; an intermittent series of exposures gives a lower photographic effect than the same amount of light allowed to act continuously. Two general methods have been used to secure a continuous time-scale: in the one (*a*), a shutter with a series of slots, the sizes of which are in any desired ratio, is moved before the sensitive surface at a uniform velocity; (*b*) in the other, a shutter is made to move across the sensitive surface by a series of impulses, each of which causes it to move a fixed distance at very high velocity, the time intervals between the applications of the impulses being adjusted to give a series of exposure-times increasing, e.g., by 2, or $\sqrt{2}$, or $\sqrt[3]{2}$. For the mechanical realization of these principles in both relatively simple and more complex and precise methods, the reader is referred to the literature cited.

Intermittent time-scales are very conveniently arranged by means of a rotating sector-wheel, i.e. a disc having a series of contiguous slots of increasing aperture. Proposed in 1840 by Claudet, it was adopted by Hurter and Driffield in their investigations. They used one with nine steps, the aperture doubling from the periphery to the centre. Scheiner used a continuously increasing aperture, modified by J. M. Eder to a series of steps in ratio $1 : 1{\cdot}27$, which gives a greater number of points over the same exposure range. A narrow interval such as this is valuable in precise study of the characteristic curve, particularly for positive material and the theory of tone-reproduction. For accurate sensitometry, however, all intermittent scales suffer from the " intermittency effect ", the failure of the plate to gather up completely the effects of discontinuous illuminations. Fig. 27 illustrates the nature of this effect, which varies greatly, however, with different plates. The effect increases with the ratio of rest to exposure, and hence is specially noticeable with short exposures (see fig. 27). Odencrantz finds that intermittent exposure gives a more definite straight-line portion.

The Density-exposure Function.—The utility of the density D, i.e. $\log_{10}O$, as a measure of the photographic effect is twofold. On the one hand it is, with certain limitations, proportional to the mass of reduced silver per unit area, i.e. to the photochemical effect—including any " afteractions " such as may arise in development. On the other hand, the physiological measure of light, as brightness-value, is found to follow the Weber-Fechner law connecting measure of sensation with stimulus, within certain limits, that is, it is a

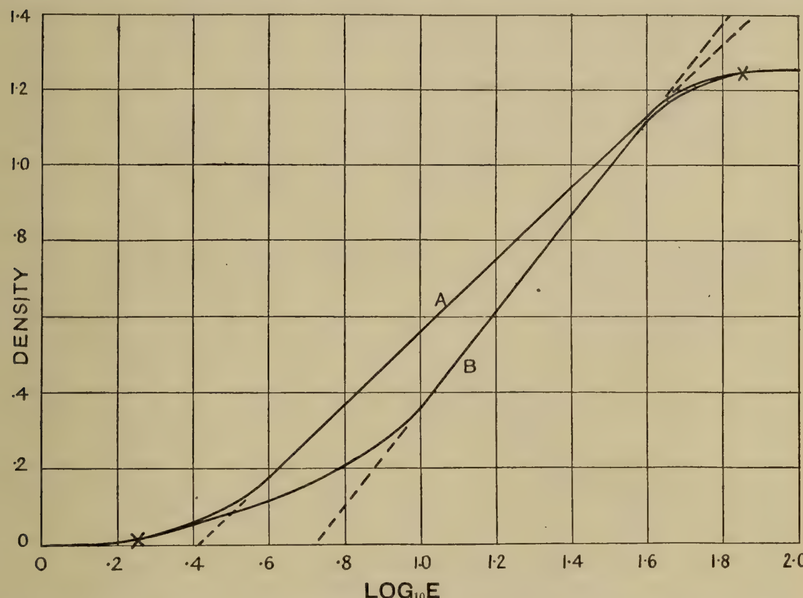

Fig. 27.—Showing Effect of Continuous and Intermittent Exposure on Characteristic Curves for Papers

A, Continuous. B, Intermittent

linear function of the logarithm of the physical light-intensity over a certain range. A series of densities, *increasing in arithmetical progression*, *hence transmitting light in geometrical progression*, gives a uniform transition from light to shade. Suppose the densities resulting from a series of increasing exposures (amounts of light) to increase proportionately with the exposures, the resulting gradation of light transmitted would appear harsh and inharmonious. Hurter and Driffield were the first to point out that this condition of affairs corresponds to the case of *underexposure* in a positive transparency, or in a negative. In the former case, the inharmonious gradation is observed directly; in the latter, " the light transmitted by the

negative would be a geometrical progression, and would, of course, by the same law [density proportional to the exposure] produce a geometrical progression of silver on a positive, . . . which would look a terribly false representation of the original".

Actually the initial action of light on a plate is to give densities in linear relation to the exposure, but this passes over into a region where the densities increase as the logarithms of the exposures. Beyond this again the density increases at a decreasing rate, reaches a maximum, and ultimately tends to *decrease*; we pass from the region

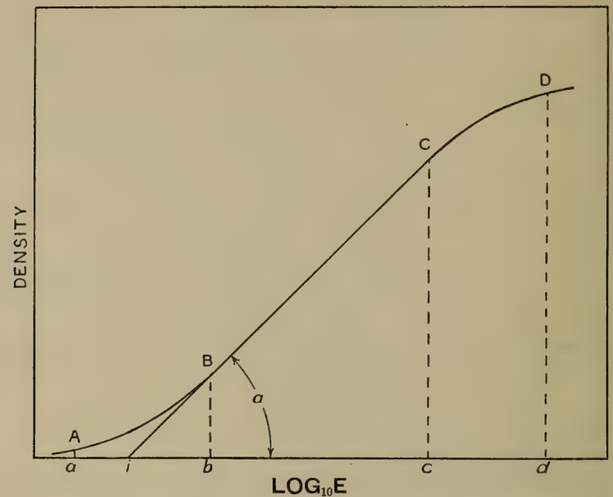

Fig. 28.—The Value I, the Inertia in C.M.S.; its Reciprocal 1/inertia gives the H. and D. Speed (when multiplied by 34)

of overexposure to that of reversal. These successive stages are shown in the curve in fig. 28, in which density is plotted as a function of $\log_{10}E$—assuming for the present the reciprocity law, $E = it$.

Various attempts (1) have been made to deduce, from physico-chemical premises, a single function representing the whole, or at any rate the part up to the maximum, of this curve. These premises involve consideration of the rate of photochemical reaction already noticed on p. 111; the more important developments are summarized in the synopsis on the following page.

For fuller details the reader is referred to the literature cited.[1]

[1] Particularly F. E. Ross, "On the Relation between Photographic Density, Light Intensity, and Exposure Time", *Journ. Optical Society of America*, **4**, p. 255 (1920).

Assumptions.	Differential and Integral Forms of Equation deduced.	Remarks.
Elder: the silver halide made developable per unit time is assumed proportional to the mass unaffected and the intensity of incident light.—(Intensity law.)	$\frac{dx}{dt} = k\mathrm{I}(\mathrm{A}-x)$ $\mathrm{D} = \mathrm{D}_m(1-e^{-k\mathrm{I}t})$	D_m determines the height of the curve, k its position along the exposure axis, and therefore the "speed". The function does not fit actual curves well.
Hurter and Driffield: the silver halide made developable per unit time is assumed proportional to the light absorbed and the mass unaffected.—(Absorption law.)	$\frac{dx}{dt} = \frac{(1-\mathrm{R})}{b}\mathrm{I}(e^{-kx}-e^{-ka})$ $\mathrm{D} = \gamma\log_e[\mathrm{O}-(\mathrm{O}-1)e^{-b\mathrm{I}t}]$ where γ is the development factor, and O the opacity of the emulsion to the active light.	The function has three parameters and fits curves better, but Ross has shown that the absorption law is incorrectly applied.
Ross: (*a*) the silver grains are assumed divisible into n groups, each group following Elder's equation. (*b*) The silver-mass is the same for each grain. (*c*) The sensitivity factors of groups are in geometrical progression.	$\frac{dx}{dt} = k\mathrm{I}(\mathrm{A}-x)$ $\mathrm{D} = \mathrm{D}_m\left[1-\frac{1}{n}\sum_{s=0}^{s=n-1} e^{-kr^s\mathrm{I}t}\right]$ Here D_m is the maximum density; n, the number of groups of grains; s, the sensitivity factor; and r the ratio of group sensitivities.	This is a polynomial form of Elder's equation; it fits some types of curves fairly well, but premises are still somewhat too simple.

Reversal.—None of the functions dealt with allow for the remarkable reversal period, and those explicitly developed to cover this usually require certain very artificial and *ad hoc* hypotheses, such as the assumption of successive "developable" and "undevelopable" subhalides. The facts as to reversal by prolonged or excessive exposure are in agreement with the view that it is caused by excess of released halogen, e.g. bromine, which attacks the superficial latent image, reducing the developability of the more exposed grains, in which halogen from the interior of the grain rehalogenizes the first formed surface silver nuclei. The action of halogen absorbents, such as hydrazine, in delaying reversal, is in agreement with this. *In scientific photography, reversal is of importance in connection with the photography of intense sources, such as the sun, spark discharges, lightning, &c.* The so-called Clayden effect—reversal in lightning flashes—is probably simply a case of normal reversal in which

excessive exposure is due to high intensity. For an explanation of certain other forms of reversal the reader is referred to papers by W. B. Bancroft.

Reciprocity Law Failure.—The failure of the reciprocal condition, D = f(E), where E = it, is of considerably greater immediate importance than reversal both for photographic theory and for scientific applications such as photographic photometry. Schwarzschild (1) proposed as experimentally satisfactory the equivalent relations

$$D = f(it^p) = \phi(i^{\frac{1}{p}}t),$$

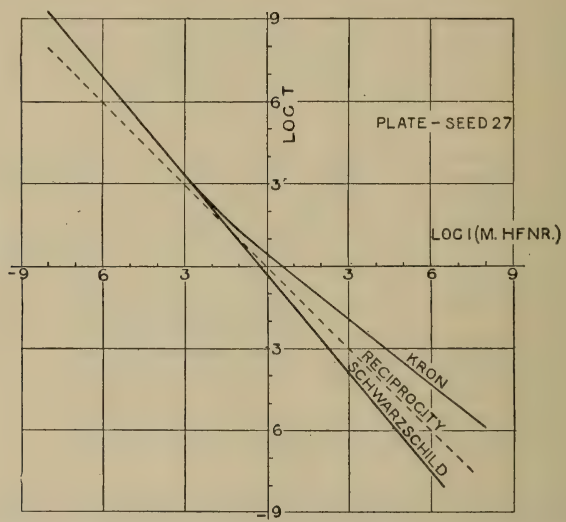

Fig. 29.—Various Exposure Products giving same Photographic Effect (Density)

i.e. the independent variable is regarded as either a product of *intensity* × *time* to the pth power, or the product of the *intensity* to the $1/p$th power × *time*, where p is a coefficient less than unity (Bunsen-Roscoe law), which varies for different plates. E. Kron (2), however, finds p must be replaced by a function of i itself, and proposes the formula

$$E = it \times 10^{-a\sqrt{(\log_{10} I/I_0)^2 - 1}}$$

in which a and I_0 both depend upon the emulsion. For low intensities this law becomes identical with Schwarzschild's, but deviates considerably at high intensities. The relations between these various proposed " exposure products " are shown in fig. 29.

If Kron's results are correct, the reciprocity law holds fairly well between intensities of 1 candle-metre and 0·001 candle-metre, but not for higher or lower values; whereas if Schwarzschild's law is correct, the reciprocity law does not hold for any intensity, the error being the same percentage of all intensities. F. E. Ross (1) gives as a practical example the following. Suppose a certain density is produced and an equal density is required with a hundredfold intensity, then, assuming $p = 0{\cdot}83$, the exposure-time necessary must be 2·4 times that computed from the reciprocity law.

It has been pointed out by Renwick and others that if characteristic curves are plotted for the same plate for an intensity-scale and a time-scale respectively, the ratio of the *gammas*, at the same time of development, will be equal to p, if Schwarzschild's law holds, i.e. $p = \frac{\gamma_i}{\gamma_t}$. The whole of this important subject requires more experimental work.

Photometers and Densitometers.—Photometers specially adapted for the measurement of photographic densities may be conveniently termed densitometers. Hurter and Driffield used a modified bar photometer, with two constant light-sources at a fixed distance, and a photometer head (i.e. a Bunsen grease-spot with mirrors) moved to and fro between them. One light-source was obscured by the density to be measured, balance obtained by shifting the photometer head, and the density calculated from the inverse-square law. The bar form of densitometer has been greatly improved by F. F. Renwick and W. B. Ferguson, who have arranged to use but one light-source and a Lummer-Brodhun photometer head (fig. 30).

For a full description of this and other photometers, reference must be made to the technical literature. The photometer is to the scientific side of photography what the balance is to chemistry. It is important to note that the density, $D\left(= \log_{10}\frac{I}{I_o}\right)$,[1] is by no means independent of the instrument and method of illumination. Hurter and Driffield's application of the Lambert-Beer law of absorption in homogeneous media to the photographic negative was criticized early by Abney and Chapman Jones, who pointed out that the silver deposit is a light-scattering medium. This subject has been most

[1] See p. 144.

completely investigated by A. Callier and F. F. Renwick. The former showed that densities measured with parallel rays ($D_{||}$) differ markedly from those measured by completely scattered light, e.g. by placing the negative image in contact with opal glass (D_{μ}). Renwick has shown that, even in this case, the apparent density is reduced by inter-reflection between the surface of the opal glass and the negative. The inter-reflection may be obviated by optically uniting the two surfaces with cedar oil.

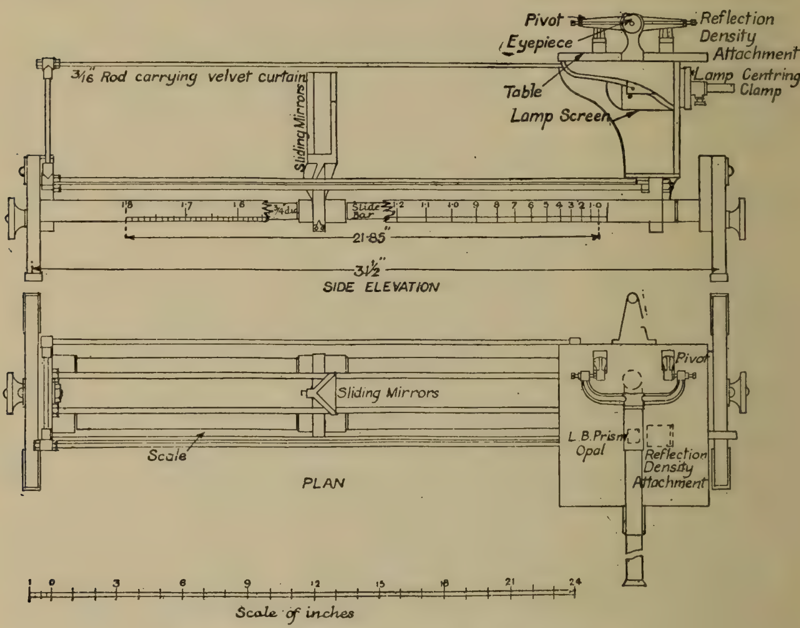

Fig. 30.—Photometer used in Photographic Work

The Wedge Method of Sensitometry.—Graded neutral-tint wedges were used by Abney in photometry and photographic sensitometry as a means of reducing light-intensity quantitatively. A simplified procedure for their production was developed by E. Goldberg in 1909, and several very interesting and valuable applications to photographic sensitometry have since been developed. R. Luther's method of obtaining the characteristic H. and D. curve is particularly elegant and instructive. It is practised as follows: a neutral grey wedge is taken of square shape and known gradation, e.g. increasing in density from 0 to 6 over 5 in., which gives an inten-

sity-range of transmitted light from 1 to 1,000,000, and has a "wedge-constant" of 1·2 per inch. The plate to be examined is exposed to a standard light behind this wedge and developed, preferably to a high contrast. The completed negative is now placed over the same wedge, but so that lines of equal density (isopaques) in each are at right angles to each other. Observed by transmitted light, the characteristic curve is seen as a rather diffused boundary, which may be regarded as either a curve of identical density, or a curve of points of equal contrast.

In the negative, the density D_n is a function of the abscissa only, i.e. $D_n = \phi(x)$, x being the abscissa. In the neutral wedge, the density D_w is proportional to the ordinate, i.e. $D_w = ay$, where a is the wedge-constant. On superposition, the resulting density D_k is given by $D_k = D_n + D_w = \phi(x) + ay$, and the positions of points (x, y) having the same total density C are given by the equation

$$\phi(x) + ay = C;$$

hence, as shown by transforming to

$$\begin{aligned} y &= \frac{c}{a} - \frac{1}{a}\phi(x) \\ &= \frac{c}{a} - \frac{1}{a}D_n, \end{aligned}$$

they give a curve the ordinates of which are proportional to the densities of the negative plus a constant. The multiplying factor, as well as the constant, depends on the wedge-constant and the numerical value of C.

These curves of equal contrast may be made visible by printing on a suitable surface. For this it is preferable to use a hard or "contrasty" process emulsion, and, as shown by G. I. Higson, instead of using repeated reproduction, to sharpen the boundary by printing from the first reproduction on to contrasty gas-light paper, locally reducing the boundary with a ferricyanide reducer. Higson has also pointed out the advantage, for special purposes—e.g. according as part only, or the whole of the characteristic curve is required—of using exposure-wedges of differing "constant" from that of the photometric wedge.

The resulting prints (see fig. 31) may be scaled by impressing a scale on the transparency in the first printing, one of the unit lines (of the $\log_{10}I$ scale) being made coincident with a position line on the plate for which the exposure is known. This is conveniently made 1, 10, 100 cm., so $\log_{10}I = 0$, 1, or 2, &c.; keeping exposure-times

to a similar scale, the exposure-scale becomes a convenient $\log_{10}E$-scale. Densities, in the vertical direction, are measured from a line of zero density which is obtained by scraping off gelatine on a straight strip on the edge of the negative alongside the smallest density. The density-readings will only agree with visual photometric densities in the absence of any spectral selectivity.

Partial applications of this wedge method of sensitometry may be made, depending upon the properties of " crossed wedges " used

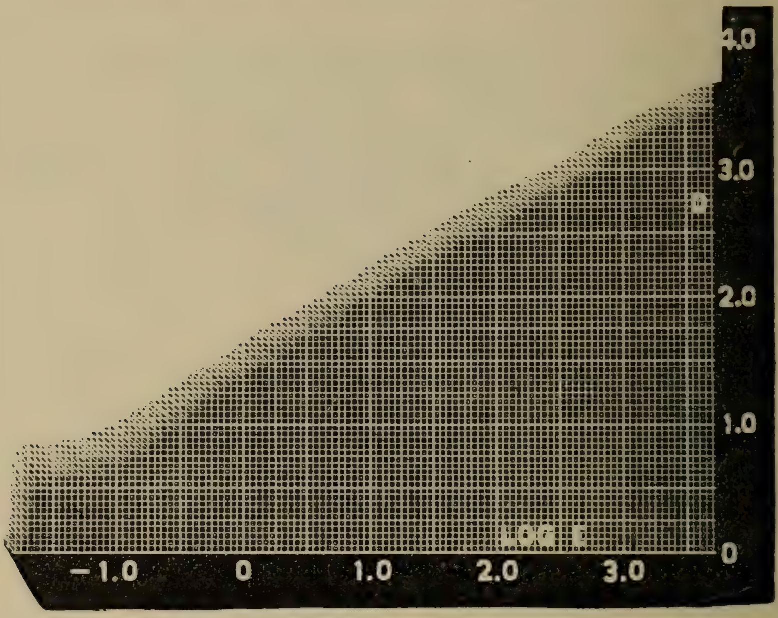

Fig. 31.—Wedge Sensitometer Curve

in conjunction with a photometric method instead of a photographic method of evaluation. Such applications are described by A. Watkins, who has described an instrument for measuring gamma and for " central speed " determination, that is, by location of the central point of the straight line part of the H. and D. curve. An instrument for the study of gradation and the measurement of gamma is described by F. F. Renwick; it depends on the fact that when two crossed wedges are revolved on each other, a position is reached when the slope of the shallower wedge balances that of the steeper. The cosine of the angle of revolution, from the crossed position to that of balance, photometrically observed, equals the ratio of steepness of the shal-

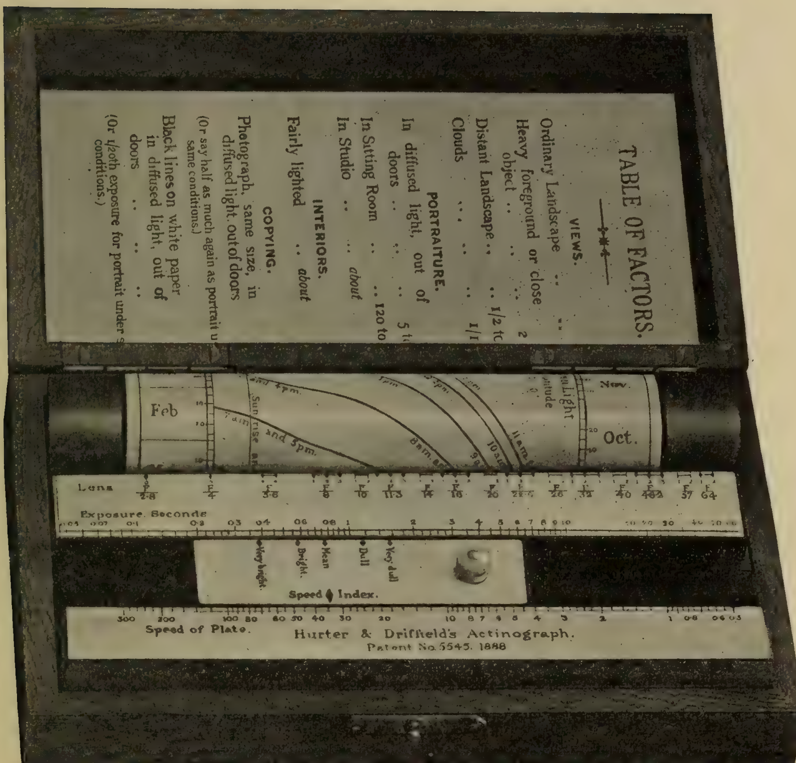

Fig. 32.—Hurter and Driffield's Actinograph

Facing p. 184

lower to that of the steeper wedge. If the wedge constant or steepness of the latter is known, gamma is obtained from a single measurement.

Actinometry.—The complement to sensitometry is *actinometry*, i.e. the measurement of photochemical illumination. Theoretically this involves measurement of both the total energy flux and its spectral distribution for natural and artificial light-sources, but practically it reduces to the determination of photographically active light (defined by the sensitivity of some standard material). In actinography, actinometric data are recorded in tables or curves for the time of year and the hour of day, for daylight at a given latitude. Qualified by weather-factors (for sunny, cloudy, or overcast conditions, and by subject-factors (seascape, landscape, &c.), they are arranged in the form of *exposure-tables* or as slide-rule calculators, with provision for lens diaphragm-values and plate-speeds. " Exposure "-time in seconds can then be found or calculated from an equation of the type:

$$\text{Exposure-time} = \frac{\text{diaphragm number} \times \text{subject-factor}}{\text{light-value} \times \text{plate-speed}}.$$

(See fig. 32.)

With field-actinometers (Watkins, Wynne, &c.) an actual test of the light is made by measuring the time which a standard piece of sensitized paper (silver bromide plus potassium nitrite) takes to darken to a standard comparison tint, measurement being made of the light falling *on* the subject. This actinometer reading in seconds is then used in conjunction with a slide-rule arrangement of diaphragm-values and speed-numbers to give the exposure from the equation:

$$\text{Exposure-time} = \frac{\text{diaphragm} \times \text{actinometer-time}}{\text{plate-speed}}.$$

The following table of plate speed-numbers is taken largely from A. Watkins. The Chapman Jones " tablet " and the Scheiner values are numbers corresponding to the lowest impression visible on development. The H. and D. speeds are obtained by dividing 34 by the " inertia ", the inertia being measured in candle meter-seconds. Watkins's speeds are approximately 3/2 H. and D. Watkins's original standard was such that 1·0 (unity) is a speed such that with full summer sun and $f/8$ stop the correct exposure would be 2 sec.

SPEED NUMBERS OF PLATES

Rating.	H. and D.	Watkins.	Wynne.	Scheiner.	Chapman Jones.
Very slow	7·5	11	F22	2	15·3
	11	16	F28	3·5	16·0
	16	22	F32	5	—
Slow ..	22	32	F39	6·5	18·0
	32	45	F45	8	—
	45	65	F56	9·5	—
Medium..	65	90	F64	11	20·0
	130	180	F90	14	24·0
	180	250	F111	15·5	25·0
Rapid ..	250	350	F128	17	—
	350	500	F156	18·5	—
Ultra-rapid	500	700	—	—	—
	700	1000	—	—	—

For very low intensities of light, exposure-time is not simply inversely proportional to the light-value. It must be corrected in consideration of conditions discussed previously (p. 180).

Tone-reproduction.—The properties of neutral-tint wedges and wedge-sensitometry form a useful introduction to what is perhaps the chief purely photographic application of sensitometry, viz. the problem of tone-reproduction. By " tone " we shall understand here the variations from light to shade in a subject, or the gradation of luminosity, apart from colour. The problem is the central one of photographic theory, fundamental for practically every application, but can be only touched upon. Concretely initiated by Hurter and Driffield, in their definition of a perfect negative, and their division of the characteristic curve into periods of under-, correct, and over-exposure, it remained for some time neglected. Recently it has been very fully investigated by F. F. Renwick, L. A. Jones, and others.

Range of Tones in Subjects.—Physically tone may be taken as equivalent to light-intensity or *photometric brightness*, whether this be intrinsic or reflected. Physiologically it is *apparent brightness* that matters, which can be conveniently treated as physical *brightness* modified and interpreted by the human eye. The physical range of tones in a subject, i.e. its overall contrast, may be photometrically determined. In ordinary landscapes a range up to 1 : 10 is low (a flat scene); 1 : 30 or 1 : 40 is a normal contrast; 1 : 60

and upwards high; 1 : 250 extreme. For indoor subjects Jones finds 1 : 60 typical of portraiture, but in engineering subjects, photographs of apparatus, &c., the contrast may easily rise to 1 : 100.

Capacity of Positive Processes.—Given such overall contrasts, the question obviously rises, what is the capacity of positive (printing) processes? Have they a range of tones capable of covering the subject-range? For gas-light or developing-out papers, Renwick finds for matte papers 1 : 20, as the range between maximum black and blank papers; for glossy papers up to 1 : 50. Jones finds that papers for amateurs have but a short scale, 1 : 5 to 1 : 20; papers for professional portrait work 1 : 40 to 1 : 60, the maximum scale possible. Renwick finds with glossy P.O.P. a range of tones up to 1 : 200. Taken overall then, the printing processes available have scale or capacity values embracing normal ranges of tones in the subject. The question then becomes, how far are they capable of correctly representing the actual tone-gradation?

Limits of Correct Rendering.—The limits of correct rendering are fixed by the straight-line portion of the characteristic curve of the printing-paper or transparency. Precise reproduction of the tone-values of the negative, and consequently of the subject, is limited to this. Actually the range of reflecting powers in a printing-paper lying in this region is much less than the overall range (or scale) noted above, hence correct or proportional rendering has to be sacrificed at both ends of the scale. We may pass on, therefore, to a closer consideration of what constitutes correct rendering and exact reproduction of any (limited) range.

Law of Tone-reproduction.—Limiting ourselves still to the sole aspect of physically or photometrically exact reproduction, it is evident that we must find a method expressing the relations which must hold between the characteristic curves of the negative and positive materials for *any*, including the exact, reproduction of the tones of the original subject. Graphical methods of exposition of this point have been worked out by Porter and Slade, Renwick, and Jones. We shall give Renwick's method, as being very concise and joining up with the earlier discussion of optical wedges. Renwick assumes as a conventional " subject " an optical wedge of known constant and range. A negative material exposed behind this subject is exposed to a known continuous range of exposures. The deduction of the relations of reproduction cannot be given more succinctly than in this author's own words: " To every point on the exposure-axis of the characteristic curve there will then corre-

spond a known $\log_{10}E$ and a known density-value, while a length between any two such values will represent a known density difference or contrast and an equal but opposite $\log_{10}E$ difference.

$$\text{For} \quad D_1 = \log_{10}\frac{I_o}{I_1}; \quad D_2 = \log_{10}\frac{I_o}{I_2},$$

$$\text{hence} \quad D_1 - D_2 = \log_{10}I_2 - \log_{10}I_1$$
$$= \log_{10}E_2 - \log_{10}E_1,$$

where I_o is the incident light-intensity, I_1 and I_2 the transmitted intensities, and D_1 and D_2 the corresponding density-values at any two points."

Case I.—In fig. 31 let the two continuous curves represent the

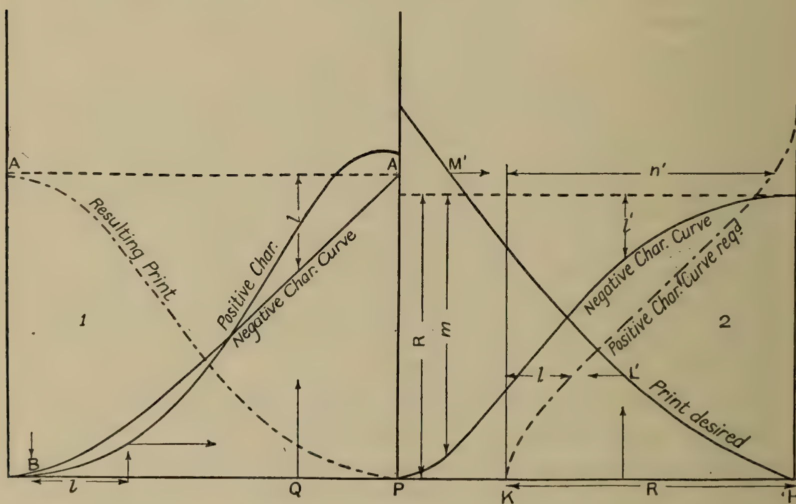

Fig. 33.—Tone-reproduction Diagram

characteristic curves found for the negative and positive materials to be used. It is desired to deduce from them the gradation-curve of a positive print made under the same conditions (development, &c.) as were employed when these curves were obtained.

Assume that it is intended just to preserve a pure white (or clear glass) under the greatest density in the negative; then such an exposure must be given that the lower limit of the characteristic curve (below B) of the positive material is employed to reproduce the tone corresponding to the point P in the original.

All points on the required curve—dotted in the diagram, fig. 33 (1)—are now easily fixed in the following way: Consider any point Q on the original wedge; the length l lying above this point between AA and the negative characteristic curve represents the density difference, and *therefore the* $\log_{10}E$ *difference* available for printing. Measure off l along the exposure-axis from the starting-point B; read off the density-value on the positive characteristic curve above the point so found, and transfer it as an ordinate to the point Q; and so on for as many points as desired.

Case II.—In fig. 33 (2) let the continuous curves represent the characteristic curve of the negative material and the desired gradation of the finished print respectively. It is required to find what form of characteristic curve for the positive material would be necessary to obtain the desired result. The total density-range of the negative is represented by the height R on the ordinate scale; hence the total $\log_{10}E$ range of that part of the positive characteristic curve which concerns us is represented by an equal length on the exposure-axis. For the sake of clearness this has been set off from the right side of the diagram as HK.

No density being required in the print where the least exposure is given, the characteristic curve starts at K, with zero density. All other points are easily deduced, as shown for L′, M′, thus: Since the lengths l' and m' represent density difference (and therefore $\log_{10}E$ differences) in the negative by means of which the densities L′ and M′ respectively are to be secured in the print, it is clear that the characteristic curve of the positive material must have values equal to L′ and M′ at the $\log_{10}E$ values distant from K by the lengths l' and m' respectively.

It is equally easy to deduce a negative characteristic curve, given the positive characteristic curve, and the final print.

The simplest condition for correct reproduction deducible from the diagram is as follows:

Suppose the slope at any point of the various curves be denoted by:

G_n = slope of negative characteristic,
G_p = slope of positive characteristic,
G_r = slope of reproduction.

Then generally, $G_n \cdot G_p = G_r$. But for exact reproduction G_r should equal 1·0, hence the condition for this is given by $G_n \cdot G_p = 1{\cdot}0$. For the straight-line portions $G = \gamma$, and this reciprocal relation then becomes $\gamma_n \cdot \gamma_p = 1{\cdot}0$, but this special case is

of little value because of the short straight-line region of most positive materials.

For a very complete discussion of the whole subject, papers by L. A. Jones should be consulted.

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SECTION VI.—THE REPRODUCTION OF DETAIL AND THE STRUCTURE OF THE PHOTOGRAPHIC IMAGE

We have now to briefly review a subject of great interest to every practical photographer, but vitally important for certain scientific applications. In spectrophotography, in photomicrography, in astronomical photography, the possibility of exact reproduction of minute detail, such as the resolution of compound spectral lines, of cellular structure, of double stars and faint nebular masses, is demanded of the photographic process. Supposing the optical system employed the most suitable, what limits and conditions does the photographic material and process impose? Further, what limitations do these place upon exactness of measurement of linear and angular intervals?

Resolving Power and Sharpness.—The *resolving power* of photographic plates may be defined as the distance between two closely adjacent images, e.g. lines which can just be distinguished. It is more convenient to express it as the reciprocal of this distance. Thus if two parallel rectilinear images of equal width are separated by a distance d, just equal to the common width of the lines, we may express the resolving power numerically as the number of lines per millimetre, so that $R = \frac{1000}{2d}$. d is usually expressed in microns.

Wadsworth considered that two lines could just be resolved if the distance between their centres was four times the diameter of the developed silver grain of the negative, for which he assumed values between 0·005 mm. and 0·025 mm.

Mees investigated the resolving power by photographing the reduced image of a fan-shaped black-and-white grating (see fig. 34), and measuring the extent to which the lines were resolved. At the same time the *irradiation*, i.e. the diffusion of light, in the plates used was studied by photographing an illuminated slit covered by a neutral wedge and varying the intensity from 1 to 60 along the

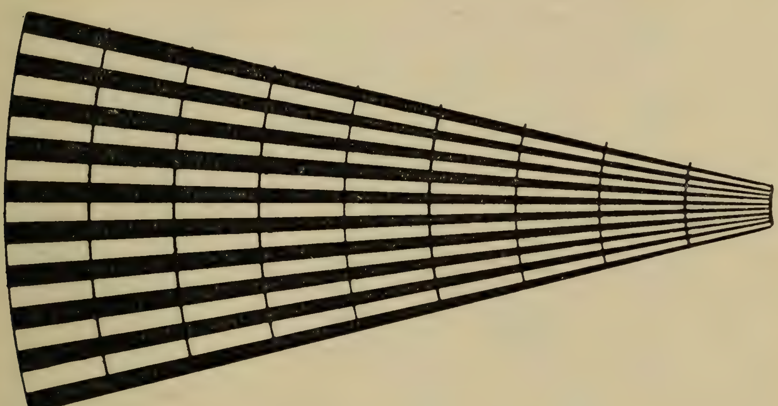

Fig. 34.—Mee's Fan-shaped Object, used for Tests of Resolving Power

slit, which was reduced, in photographing, some twenty-two diameters. Images of " tadpole " shape were obtained, the spreading increasing with the light-intensity. It was shown that the resolving-power of a plate depends upon the irradiation, which is not directly proportional to the size of the silver halide grain, but is affected both by interreflection and diffraction.

This spreading of the image, or lateral growth due to irradiation, had been investigated by astronomers and used as a basis for a method of stellar photometry. Scheiner obtained a formula connecting the diameter of the image with the *exposure* of the form $\Delta = a + b \log_{10}E$, whereas the British astronomers at Greenwich developed the formula $\Delta^{\frac{1}{2}} = a' + b' \log_{10}E$, Δ being the diameter of the image, E the exposure, and a and b constants; also a' and b' constants.

It has been shown that whereas the former is valid for a range of exposures of about 1 to 500, the latter holds for the much wider

range of approximately 1 to 15,000 (fig. 35). It has been pointed out by Ross that the *Scheiner formula* implies that the scattering of light at the edge of an image can be represented by a formula of the type

$$I = I_0 e^{-\frac{1}{k}x},$$

where x is distance measured away from the edge and k is a constant; this equation is, however, nothing but the Lambert-Beer law of

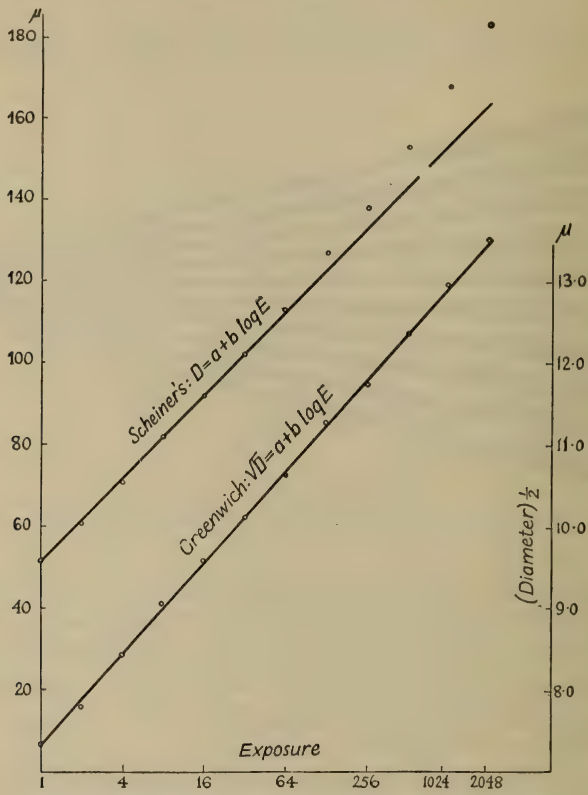

Fig. 35.—The Spreading of a Circular Image by Irradiation, &c.

extinction (see p. 111), $1/k$ being the extinction co-efficient. Such a formula can only be a first approximation and of limited validity. This fact is shown, not only by the limitation of the Scheiner formula, but directly by the important investigations of Renwick, Channon, and Bloch on the transmission of light by scattering or turbid media. However, the formula is useful as a first approxi-

mation, like the corresponding Scheiner formula, and it is important to notice that it gives a curve of distribution of density at the edge of an image which is identical in form with the H. and D. characteristic curve relating density to exposure. In other words, the characteristic curve of an emulsion is the same as the curve of " sharpness ", except that the abscissæ are compressed by a constant factor. This relation leads to a simple method for determining the sharpness from the characteristic curve (Ross, loc. cit.).

Goldberg also investigated the growth of the image produced by a small circular hole in contact with the emulsion, and given increasing exposures. The curve of *diameter* plotted against *exposures* (in fundamental units) he called the *turbidity curve*, and the slope at any point the *turbidity factor* K. This slope changes with the exposure, but not in a manner consistent with the formula found by Scheiner and Mees. No necessary relation between plate-grain and this factor was found, although the Lippman " grainless " emulsions gave K = 0; whilst coarse-grained high-speed emulsions gave great spreading. On the other hand, fine-grained bromide paper and plates also showed great spreading of the image. Goldberg identified the turbidity-factor with the reciprocal of the light-gradient measured laterally from the edge of the image.

Now we have, as a measure of contrast on development, the slope of the characteristic curve in the period of correct exposure, i.e. $\frac{dD}{d\log_e I}$. The *density-gradient* at the edge of an image, where spreading takes place, is $-\,dD/dx$, the slope of the curve obtained by plotting density against distance measured out from the edge of the image (see fig. 36).

This was termed by Goldberg the *sharpness-factor*, but may be abbreviated to *sharpness* S. Since $S = -\frac{dD}{dx}$, it is given by

$$S = \frac{dD}{dx} = \frac{dD}{d\log_{10}E} \times \frac{d\log_{10}E}{dx},$$

$$= \frac{\gamma}{\kappa},$$

or in words, *the sharpness equals the development-factor divided by the turbidity-factor.*

In fig. 37 is shown diagrammatically the distribution of light at the edge of an image, the various dotted curves representing

isophotic zones as produced for example by laying an optically sharp edge, such as a razor blade, on the surface of the plate. Actual

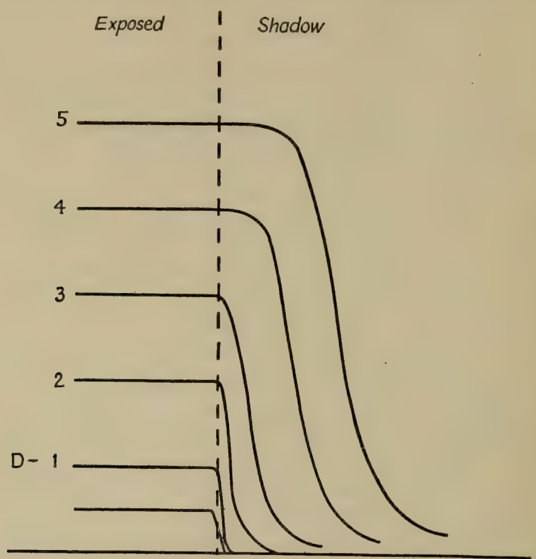

Fig. 36.—Density-gradient at Edge of an Image

density-gradients from such knife-edge images have been measured by P. G. Nutting, O. Tugman, and F. E. Ross. Space forbids a

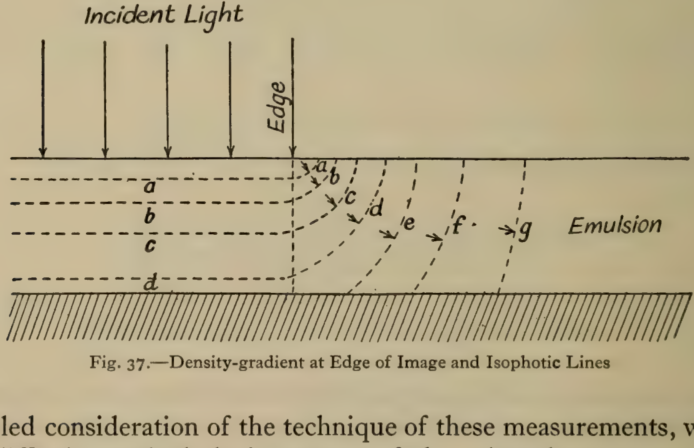

Fig. 37.—Density-gradient at Edge of Image and Isophotic Lines

detailed consideration of the technique of these measurements, which are difficult, particularly in respect of the microphotometry of the densities of the very narrow intervals into which the side-diffusion

image must be divided. On varying the time of development, it was found that the sharpness S computed from the formula $S = \frac{\gamma}{\kappa}$ only agrees with observed results for values of $\gamma = 1$, i.e. approximately near a normal development-factor. Thus:

Time of Development.	γ.	Observed S.	Calculated S.
0·75 minutes	0·71	0·123	0·085
1·5 ,,	0·16	0·114	0·139
3·0 ,,	1·48	0·121	0·178

The formula indicates the type of plate or emulsion desirable for securing sharp images. First, it should be one of high develop-

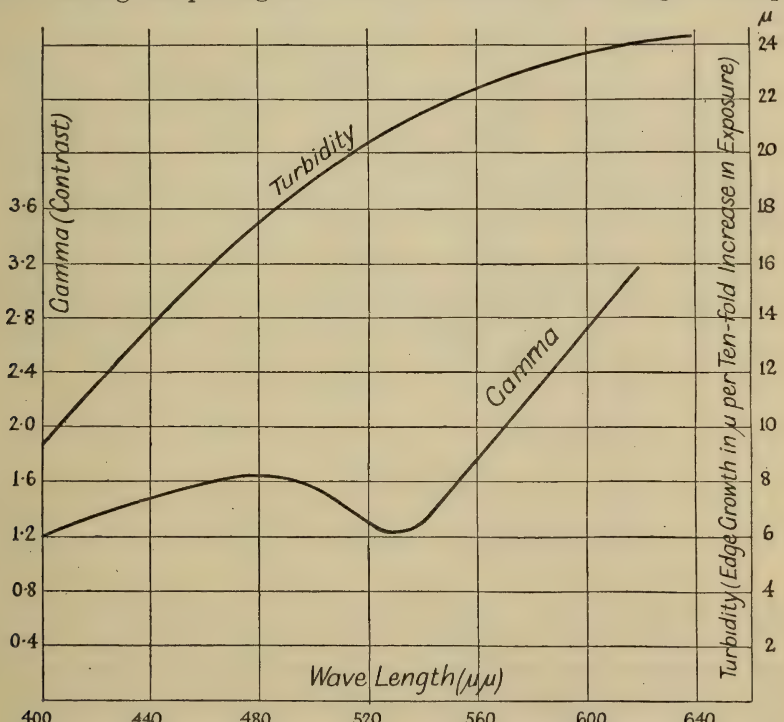

Fig. 38.—Variations of Turbidity-factor and Development-factor with Wave-length

ment-factor and of low turbidity. Secondly, it should have a characteristic curve giving a long straight-line portion, with little " toe "

to the curve, since it is important that the maximum slope to the curve be obtained at a relatively low density. These conditions are not easily secured simultaneously, since the emulsions giving the steepest values of γ are generally such as have a short straight-line portion.

Sharpness and Wave-length of Light.—Both the turbidity and the development-factor are functions of the wave-length of light

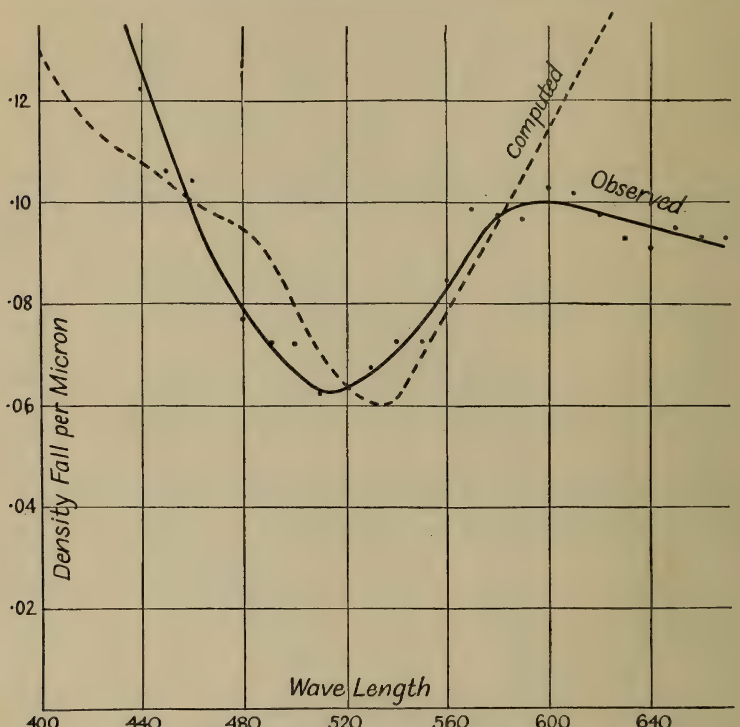

Fig 39.—Showing Variation of " Sharpness " with Wave-length

used in exposure. In a case determined by Ross, the variations of turbidity and γ with wave-length were found to be as shown in the figure (fig. 38). The combination of these curves gives the theoretical wave-length sharpness curve, which was plotted on the same diagram with the measured sharpness curve, giving the result shown in fig. 39. The agreement is fair until the red end is reached, when the divergence is marked.

Effective Resolving-power.—We can now return to the

consideration of the effective resolving-power of emulsions. The preceding discussion has shown that this is not only determined by the size of the developed grain, but by *sharpness*, which is largely controlled by the optical and photochemical properties of the emulsion. The way in which developed grain-size and sharpness may balance each other is shown in the comparison of the resolving-powers of an average emulsion with chemical and physical development respectively. Obviously the turbidity-factor is the same for both cases. The contrast-factor is quite different, however. For physical development of a Seed 23 emulsion Ross found $\gamma = 0{\cdot}5$, and for chemical development $\gamma = 2{\cdot}5$. Since $S = \frac{\gamma}{\kappa}$, we should expect the sharpness to be much greater for chemical development, and this was found to be so. Yet, on a resolving-power test, physical development gave a 20 per cent higher value than chemical development, due to the much finer grain produced by physical development.

Using the fan-shaped test-object devised by Mees (see fig. 34), the influence of developers and development upon resolving-power was investigated by K. Huse. He found that with increasing the time of development, the resolving-power rises quickly to a maximum, more or less prolonged, then drops again. Considerable differences in the maximum resolving-power were observed with different developers, pyrogallol with caustic alkali giving the highest value, 77, for the plate used, and edinol the lowest, 47. The differences with the same developer for various emulsions were as follows:

Plate.	H. and D. Speed.	R.P.
Albumen	0·01	125
W. and W. high resolution	3·00	81
Eastman positive cinematograph film	10·00	42
Seed 23	150	35
Seed Graflex	450	25

As regards effect of wave-length of light in exposure, this varies considerably with the emulsion, but in general the resolving-power appears to be high in the violet and blue, diminishes to a minimum in the green, and rises again in the red. These results are in general agreement with the variation of the sharpness S with wave-length (fig. 40).

Goldberg, in the fundamental paper already referred to, criticized the employment of optically reduced line-systems as test-objects for photographic resolution, on account of the difficulty and uncertainty in controlling the optical resolving-power of the lens-system. To estimate what he terms the " limit of resolution ", the smallest diameter of disc or width of line which can be made, he has used the following very simple and effective method. Good grade silvered looking-glass is cleared of the varnish on the backing, and innumerable fine scratches are made with a piece of emery-paper.

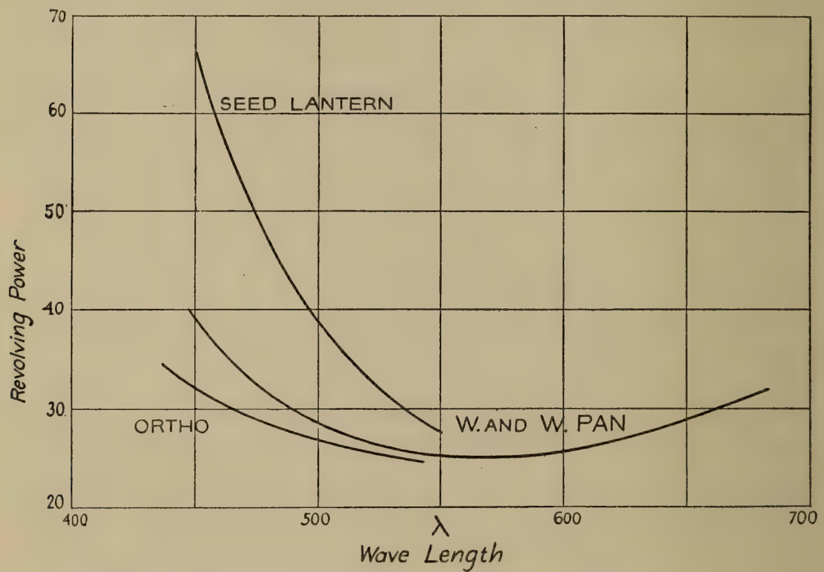

Fig. 40.—Showing Variation of Resolving-power with Wave-length

Contact exposures are made through this, with exposure just sufficient to give an impression. The resultant images allow a ready estimation of the resolving-limit to be made, different emulsions showing remarkable differences in the ability to reproduce the finest lines.

Practical Inferences.—Certain practical conclusions are drawn by Goldberg and Ross with regard to the attainment of *sharpness* and *resolution*. With ordinary or poor lenses, for the greatest sharpness it is essential to use plates with the highest contrast (γ) possible, and full development. With poor optical systems, the want of sharpness due to the resolving-power of the plate is of

minor importance compared to that due to the optical system. If an optical system of high definition is used, preferably with paraxial rays only, two limiting cases may be considered. First, where it is a question of reproducing fine lines or structures of low contrast, the turbidity-factor can be neglected, since with short exposures the spreading is negligible. The essential thing is a high limit of resolution. Second, as the other extreme, consider fine lines or points where the contrast, i.e. the difference of light intensity is very great, as in the spectrography of lines arising in astronomy. Here lines or points of enormously different intensity may be juxtaposed. Short exposures will not reproduce the low-intensity lines or points; high exposures will spread out the high-intensity ones. Hence the turbidity-factor is all important, and plates of the lowest turbidity-factor should be used regardless of resolution limit.

In respect of the last conclusion of Goldberg, Ross has pointed out that while increased sharpness (i.e. reduced turbidity-factor) may be secured by using yellow-dyed plates and exposing to violet light, thus making the penetration small, this result cannot necessarily be applied in practice, e.g. in astronomy. Experimentally, the external turbidity can be made nil, but is not controllable in astronomical photography, when it may be larger than that of the emulsion. It is then necessary to use plates with the highest contrast (γ), but yellow-dyed plates have a low contrast.

Graininess or Granulation.—The " grain " of the developed image so far considered is the size of the silver particle. The measurement must be made with a high-power microscope. Plates and films, however, on development show with low-power magnification, as used in projection and enlarging, a granulation which is objectionable in such operations. This is due to the agglomeration of primary silver grains to second-order aggregates. Again, there is often a granularity visible to the naked eye, which is due to further agglomeration of these secondary aggregates to third-order aggregates. These terms are used for convenience. Actually, corresponding to every stage of magnification—with sufficient optical resolving-power —a certain degree of granulation or " graininess " will exist. L. Jones and N. Deisch have shown that it may be measured and numerically expressed, on the assumption that G, the graininess, is directly proportional to the distance at which it becomes just visually imperceptible, this being compared with the distance at which a structure of known period, e.g. a fine cross-line screen, just disappears. Suppose a screen of 2000 lines to the inch to be equi-

valent in this way to a given granularity of the developed image, the latter may be said to have a graininess of 2000. This type of inhomogeneity of the image also influences resolving-power and the rendering of detail.

Secondary Structural Variations of the Image.—The use of the photographic plate for exact measurements of small intervals, as in spectroscopy and astronomy, involves the examination of the precision to which dimensions can be measured with it. Minor or secondary phenomena in exposure and development assume critical importance in this connection. Thus the accuracy of photographic measurements of the relative position of double stars and satellites was queried in 1906 by Khotinsky. He found an apparent repulsion between neighbouring images. On photographing a wide double star for varying times, the following results were obtained:

Exposure Time.	Diameter.		Distance between Borders.	Measured Distance between Edges.
	Star.	Companion.		
	mm.	mm.	mm.	mm.
1 min. ..	0·282	0·039	0·086	0·2467
16 min. ..	0·482	0·080	—0·014	0·2667

Thus for long exposure, with an overlap of 0·014 mm., the separation relative to that for the shorter exposure increased 0·020 mm., a deviation of some 8 per cent. Similar results were obtained by Lau, whilst other observers found both repulsion and attraction of adjacent images. Analyzing these results and the conditions of their production, F. E. Ross suggests three factors controlling the deviations:

(*a*) *A turbidity effect*, in which irradiation causes the adjacent circular images to assume an ovate form, the geometric centres being displaced toward each other. This effect appears to be masked in practice by the *development or Khotinsky effect*, but may assume large relative values for images in contact.

(*b*) *Gelatine displacement and distortion effects.*—These have been observed and studied by Ross. When pyro-metol or hydroquinone with caustic alkali are used, images *contract* by an amount depending upon the size and density of the image and on the temperature and composition of the developer. The contraction reaches a maximum for images approximately 5 mm. in diameter, and may affect the normal " spreading " of the image (as used in stellar photometry, see p. 191), so that the diameter may actually pass through a

minimum on increasing the exposure. Hydroquinone with alkaline carbonate, metol-hydroquinone, and chlor-hydroquinone seem to give images free from this effect, which is probably due to unequal drying of a "tanned" image and its surroundings. Errors due to this cause in double star measurement, or in measurements of the Einstein effect (apparent attraction of a star's image to the limb of the sun in eclipse photographs) may be considerable, as also in observations of close lines in spectrograms.

(*c*) *Development effects*, due to local accumulations of reaction-products of development and differential diffusion of the developer. In the so-called *Eberhard effect* this leads to a dependence of the density upon the size of the image, in the *Khotinsky* effect (loc. cit.) to apparent repulsion of adjacent images, which increases with exposure. This effect is particularly important in the photography of spectral lines. Ross points out that *the net result in any case depends upon a balance between opposing factors*, but that, in general, *reduction of exposure to the minimum possible is indicated as an essential precaution.*

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Section VII.—Orthochromatic and Colour Photography

In the discussion of tone-reproduction, colour differences were explicitly ignored. The photographic rendering of colour has two aspects. The more modest of these is *orthochromatic photography* —the rendering of colours in monochrome according to their visual luminosities, more or less modified according to certain æsthetic requirements. Isochromatic (equicoloured) rendering may be conveniently reserved for a reproduction independent of colour or wave-length, a condition of importance in many scientific applications of photography. The other and more ambitious aspect is *colour photography*, the reproduction of colours. The whole subject is treated fully in the chapter on "Colour Photography" (Ch. XI), so that only the basic physical and chemical principles involved will be noticed here.

Orthochromatism and Isochromatism.—Terms such as *orthochromatic* and *isochromatic* were applied to the first plates sensitized beyond the normal blue-violet region to yellow and green rays. Even with considerable sensitiveness to these, ultra-violet, violet, and blue might be disproportionately rendered, and red not at all. The elements of true orthochromatism are three:

(*a*) The visual luminosity of colours, as expressed by the (luminosity, wave-length) curve for the average eye.

(*b*) The colour, or more exactly, (wave-length, sensitiveness) curve of the emulsion, which should be approximately panchromatic, i.e. sensitive over the whole of the visible spectrum. Since the distribution of energy over the spectrum varies with different sources, this should be obtained by exposure to a light approximating to " daylight " in quality.

(*c*) The colour-screening effect, that is, the (wave-length, absorption) curve of the colour-filter used to correct the sensitivity distribution afforded by (*b*) to the luminosity curve, or other desired distribution of sensitiveness.

Adjustment and Compensation.—The visual luminosity curve for average non-colour-blind eyes (normal trichromats) varies with the absolute intensity of illumination. As will be seen from the curves (fig. 41), the maximum is shifted toward the shorter wave-lengths as the intensity is diminished. This is known as *Purkinje's phenomenon*,[1] and has been attributed to the existence of two synergic processes in vision—one for high intensities, called daylight or solar vision, chiefly limited to the foveal or central region of the retina; the other, for low intensities, twilight vision, proper to the peripheral region, and much less sensitive to colour. It is evident that what has been said with regard to the psychological factor of tone-reproduction applies at least as fully to colour rendering. For completely correct rendering, the print would have to reproduce the luminosities of the subject at the intensity of illumination- and adaptation-level of the eye by which the subject was originally seen. Actually such a rendering is seldom attempted or desired. In fact, the rendering at even high intensities is practically a compromise, since, to take a definite example, to render equally luminous reds and greens in a subject by equal densities in a print would sacrifice colour contrast entirely. The photographer's remedy in such cases is to over- or

[1] See *Colour and Methods of Colour Reproduction*, by L. C. Martin and W. Gamble (Blackie).

under-correct for a given coloured object, to adjust the rendering of a colour-contrast by suitable compensating filters.

Colour Filters and Filter Factors.—For a full discussion

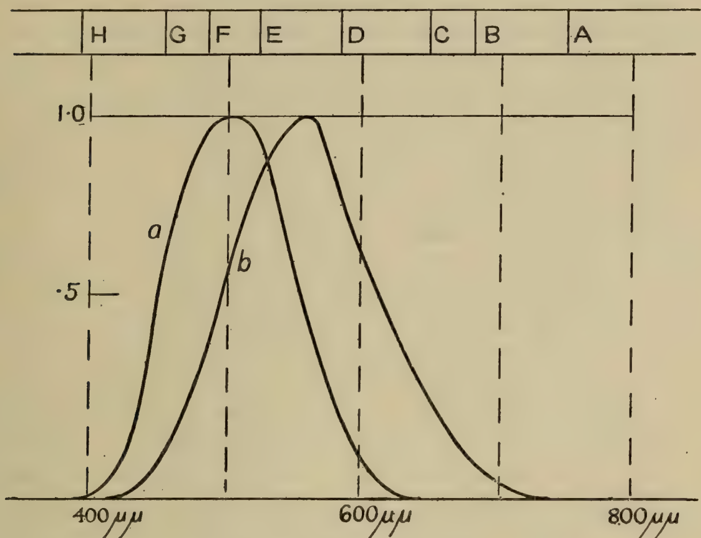

Fig. 41.—Visibility of Radiation

a, At high intensity. *b*, At low intensity.

of the adjustment of colour-contrasts and the use of filters the reader is referred to special articles and books. Any absorption-screen or filter will necessitate an increase in exposure; the ratio of the exposure, with a given filter, to the exposure necessary unscreened is termed the *multiplying factor* of the filter. Such factors are not simple characteristics of the filters, but depend also upon the sensitiveness-curve of the plate. This is readily seen by comparing the effect of a sharp-cut yellow filter used with an erythrosin sensitized and a panchromatic plate respectively (fig. 42).

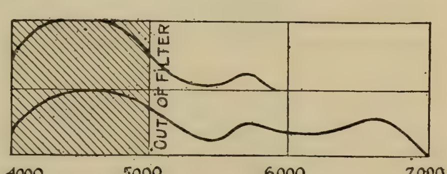

Fig. 42.—Diagram showing Filter Cut

For simplicity the filter has been supposed to cut absolutely sharply at wave-length 500 $\mu\mu$, i.e. to absorb the whole of the ultra-violet and blue-violet, and to transmit green, yellow, and red un-

diminished. In the upper part of the diagram is shown the effect of this upon a colour-sensitive plate having 97 per cent of its sensitiveness in the blue-violet, and 20 per cent in the green. The screen in question will cut out all the blue-violet, that is, 80 per cent of the effective light, and will increase the exposure forty times; it has therefore a multiplying factor of 40. In the lower part of the diagram is shown the effect upon a panchromatic plate, having, say, 87 per cent of its sensitiveness in the blue-violet, and 13 per cent in the green and red. Here the screen cuts out 87 per cent of the effective light, hence only increases the exposure eight times. The same filter has therefore a factor of 40 for one plate, of 8 for another.

Special Filters.—Filters for specific purposes, e.g. monochromatic filters for spectrophotography, contrast and detail filters for photomicrography, &c., will be described in special articles of this work. As relevant to the present subject should be mentioned monochromatic viewing-filters. These enable the photographer to eliminate largely colour differences in a subject and observe it according to the luminosities which can be rendered by a panchromatic plate or film. It should be pointed out here that the optical properties of filters are generally of equal importance with their colour properties. A filter of poor optical quality can spoil the definition of the best lens; hence filters should be tested for definition and accuracy of focus.

Colour Sensitizing.—Early colour sensitizing with eosin and erythrosin dyes only extended into the yellow-green. The introduction of the *isocyanin* dyes by Miethe, still more of the related *carbocyanins* by E. König, permitted extension of sensitiveness to the whole visible spectrum. Plates thus prepared are termed *panchromatic*. Formerly it was necessary to prepare them by bathing plates in very dilute alcohol, containing solutions of the dyes. Since these dyes are very sensitive to acids, and since they are present in aqueous solution very largely in a colloidal form little capable of diffusing into gelatine, the preparation of such plates required a careful and difficult technique. However, panchromatic plates are now obtainable commercially, and except in the case of hypersensitized and infra-red sensitive plates for special astronomical and spectroscopic purposes, it is not necessary for workers to prepare their own " red-sensitive " plates.

The gradation (scale and contrast) of ordinary plates appears to depend upon the wave-length of light. More experiment is required upon this, and upon colour-sensitive plates, since with panchromatic

plates it has been stated that the differences in gradation are hardly appreciable. This question is of great importance in the three-colour process of colour photography, and recent work indicates that considerable differences occur (see fig. 43).

Direct Colour Photography.—There are two direct methods of *photochromy*, both of which arose in the early discovery of Seebeck that silver chloride would very imperfectly reproduce the

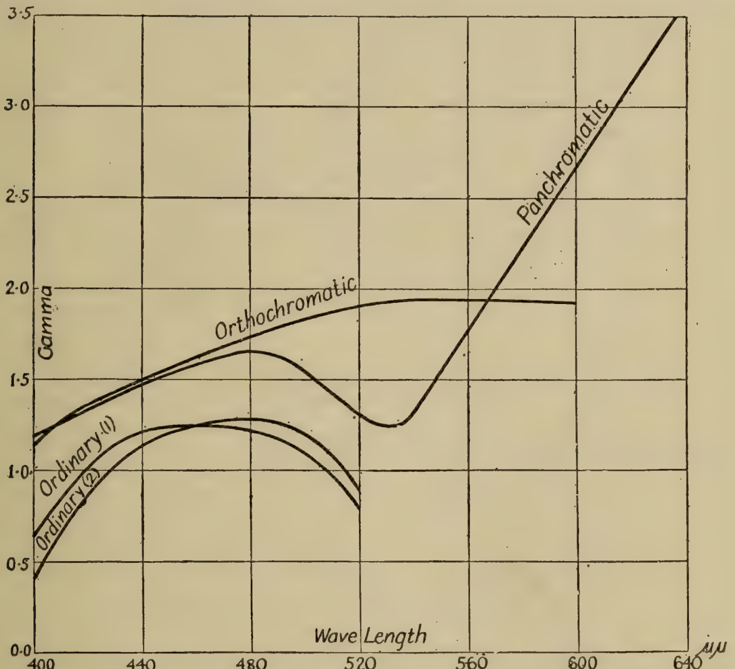

Fig. 43.—Variation of Development-factor with Wave-length

colours of the spectrum. Though historically and scientifically interesting, this property of silver chloride, more correctly of photochloride, has not itself furnished a solution of the problem. E. Becquerel reproduced the spectrum on polished silver plates faintly ' chlorized " by immersion in chlorine water. It is probable that the colour reproduction is due, in part at least, to the formation of stationary waves, as contended by Zenker, but the process is complicated by the direct formation of " bleach out " or " adaptation " colours of the photohalide. Of the two direct processes thus curiously commingled in their infancy, the one is dependent on the

physical principle of interference of vibrations, the other on the chemical principle of *mobile equilibrium*.

Interference Photochromy. — The possibility of colour photography by stationary waves of light was first definitely stated by Zenker. The development of a practicable process was achieved by G. Lippman. The physical principles underlying the process are illustrated in fig. 44.

When a wave-train encounters a medium of lower refractivity, it is reflected (partially) without retardation of phase. On the other

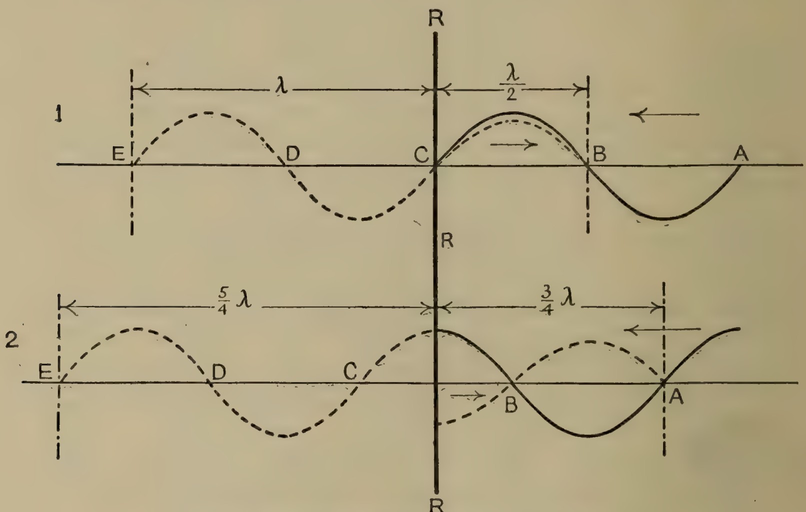

Fig. 44.—Diagram illustrating Optical Interference

hand, on encountering an optically denser medium, a phase retardation of half a wave-length accompanies the reversal of the direction. In fig. 44 (1) a wave-train ABC encounters such a medium at R. In the absence of the medium, the undulation would have progressed to E in the time t, say. But if the wave is reflected it is found that the reflected wave (dotted line) has only returned to B, instead of A, i.e. it is retarded by $\lambda/2$, where λ is the wave-length. In the lower part (2) of the figure, a further progression over $\lambda/4$ is shown; in place of the disappearing peak of the incident wave, there is a trough in the reflected wave.

Suppose the progressive wave-train is incident on a highly reflecting medium, so that it is returned with little or no loss of energy. Interference will occur between the incident and reflected wave-

trains, resulting in the formation of stationary waves. At intervals of $\lambda/2$, there will be alternate maxima and minima of light intensity. Suppose a light-sensitive medium contiguous to the highly reflecting surface, such as the " grainless " silver bromide emulsion in contact with a mercury surface, as used by Lippman. Then the photochemical change in this on exposure to light of definite wave-length will be distributed in a number of thin layers, the maxima at intervals of $\lambda/2$, the minima also at $\lambda/2$ intervals, at the nodes of the stationary waves. On development of the exposed silver bromide, these layers, at the maxima of action, are deposited as metallic silver. Each colour will establish its own system of *elementary mirrors*, partly transparent, partly reflecting. When illuminated (after fixation, drying, &c.) by white light, each layer reflects part of the incident light. For the " mirrors " separated by $\lambda/2$, where λ corresponds to red light, the red rays from successive layers will differ by $\lambda/2$ incident *plus* $\lambda/2$ reflected, i.e. by λ, and will reinforce each other, giving a red reflected ray, and similarly for other colours.

The existence of these elementary mirrors has been directly demonstrated by Neuhauss, Senior, Ives, and others, by taking photomicrographs of very thin sections of Lippman films. The distances measured between the layers agreed well with the theory.

The Bleach-out or Colour-adaptation Process.—This direct photochemical process is a development from the experiments of Seebeck, Becquerel, Poitevin, and others with photochloride. This substance gives a partial reproduction of the spectrum, but it cannot be fixed. Imperfectly stable in darkness, the colour differentiation is rapidly obliterated in white light. It is characteristically distinguished from the interference photochromy of the previous paragraph by its production in the absence of a reflecting support, and by the independence of the colours of the viewing angle. The colours are true pigmentary colours, due to selective absorption, or at least selective resonance.

It has been already stated that photochemical change is brought about by the light absorbed. Photochloride is light-sensitive over a wide range of composition, $AgCl \mid Ag : AgCl \mid Ag$, that is, between pure silver chloride and silver, but actually the sensitivity probably reaches a limit within a few per cent of silver above the limit AgCl. We can regard this sensitiveness either from the direction $AgCl \rightarrow Ag$ (darkening) or from the direction $Ag + Cl \rightarrow AgCl$ (bleaching or fading). Suppose we have the system in a stage approaching maximum absorption of all wave-lengths in the visible spectrum, i.e.

approaching a neutral grey or black. On exposure to monochromatic light the mobile equilibrium will be adjusted in the direction of making the action due to that ray a minimum. Very rapid increase of the refractivity for that ray will increase its reflection, and the system, thus selectively reflecting the incident ray, is protected from further action. If such adjustment is effected for all spectral rays, then on subsequent viewing in white light each portion previously illuminated with light of one colour will selectively reflect that ray from the white light, giving colour reproduction.

The practical development of the colour-adjustment or bleach-out process has succeeded better with mixtures of light-sensitive dyes, that is, dyes fading out to colourless (ultra-violet absorbing) substances. These are mixed to form a neutral black—generally in separate layers to avoid chemical interaction. For the practical working-out of the process by Worel, J. H. Smith, and others, the chapter on "Colour Photography" in this work should be studied.

The *indirect* or trichromatic (and dichromatic) processes are discussed fully in another chapter, and need no mention here, since they do not depend upon a simple physical or chemical basis, but on the empirical fact that natural colours can be reproduced by mixtures in given proportions of three primaries, and, imperfectly, of two.

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CHAPTER V

Astronomical Photography

The earliest star photographs were taken as far back as 17th July, 1850,[1] when W. C. Bond at Cambridge, U.S.A., obtained pictures of some of the bright double stars, whilst in 1864 Rutherford, with a specially corrected object-glass, secured photographs of the Pleiades which H. Jacoby was later on able to compare with plates taken at Lick in 1900.

It was not, however, until nearly twenty years later that astrography on a comprehensive scale was embarked upon. This was rendered possible by the introduction of the " gelatine dry plate " about the year 1878–9. In 1882 a great comet appeared in the southern skies, and photographs taken at the Cape of Good Hope Observatory under Sir David Gill's direction proved unexpectedly successful. Apart from the fine picture of the comet itself, the feature of prime interest was the number and quality of the images of the stars shown on the background.

Gill had already formed the project of extending Argelander's *Durchmusterung* to the Southern Pole, and immediately realized that here to hand was a rapid and accurate method of carrying it into execution.

With a photographic doublet lens 6 in. in aperture and 54 in. focus he set to work, his efforts resulting in the production of the Cape Photographic *Durchmusterung* containing the positions of nearly 500,000 stars to the 10th magnitude.

At the same time the brothers Prosper and Paul Henry of the Paris Observatory were engaged on the continuation of Chacornac's chart of the ecliptic zones of stars to the 13th magnitude, designed to aid in the detection of minor planets. By the old laborious method of charting at the telescope a considerable portion had been completed, but on reaching that part where the Milky Way and the ecliptic intersect, they found their task nearly impossible, the stars

[1] *Harvard Annals*, Vol. XXVI.

being so densely packed. Photographic charting promised a solution of the difficulty, and on 11th May, 1885, they announced to the Paris Academy of Science the success of some preliminary experiments made with an instrument constructed by them for the purpose.[1]

These results suggested the undertaking of a general photographic survey of the heavens, and on 16th April, 1887, an international congress met in Paris to discuss measures and organize action. They resolved on the construction of a chart of the whole heavens which would contain all the stars down to the 14th magnitude. In addition, a supplementary series of plates was to be taken with shorter exposures, showing stars to the 11th magnitude. These latter were to be measured and the results published in a catalogue. The photographs were to be taken with telescopes similar to that designed by the Henrys, thus providing for uniformity in scale and light-power.

The undertaking, obviously beyond the resources of one observatory, was distributed in fairly equal portions among eighteen observatories scattered over the world. Some of the observatories commenced work without delay, and with the necessary energy and funds have completed their allotted portions; others, however, were not so fortunate, and the great scheme has not yet been carried to completion.

The Astrographic Telescope.—An astrographic telescope consists essentially of a twin telescope equatorially mounted in order to allow for the diurnal movement of the stars, with a reliable driving clock which will keep it accurately pointed to the object being photographed.

One objective is photographically corrected, and the rays are received on the photographic plate.[2] The other, visually corrected, is the object-glass of the guiding telescope, by which the observer " sets " on the object and during the exposure corrects irregularities in the following of the instrument, and ensures that the telescope is directed accurately to the same part of the sky throughout. In the standard telescope adopted by the Paris Conference the photographic objective has an aperture of 0·33 m. or 13 in., and focal length 3·43 m. or 135 in., covering a field 2° square on a scale 1 mm. = 1 min. of arc. The lens is corrected as regards spherical and chromatic aberration for rays near wave-length 4300, and special attention is paid to the fulfilment of the " sine condition ". The last is very important, as otherwise the lateral images will be affected by coma,

[1] *Comptes rendus*, Tome 100, p. 1177.

[2] The physical chemistry of astro-photography is discussed on p. 190, *et seq.*

causing a displacement of the apparent centre varying with the intensity of the image. The guiding telescope, of equal focal length, is bracketed rigidly to the photographic telescope at both extremities as well as at the centre, thereby avoiding the suspicion of differential flexure. The eye-piece is mounted in cross-slides, by which it may be moved to any part of the field where a suitable guiding star is to be found.

Adjustment of the Telescope.—An undistorted stellar photograph is the projection of the celestial sphere on to a tangent plane—the photographic plate. The plate must be normal to the principal axis of the lens, which should also pass through its centre. To this end the objective is furnished with three tilting screws, and the plate also rests on three adjustable bearings. This adjustment is made with the aid of a small collimating telescope mounted on a triangular base with three adjustable legs. It carries in its focal plane a graduated graticule which serves as a micrometer. The centre of the objective may be indicated by sticking a small paper spot on the outer surface, or by stretching two strings from edge to edge at right angles and intersecting at the centre. The centre of the plate is shown in the same way. Placing the collimator on the surface of the objective at its edge, and looking down the tube at the plate placed in the focal plane, the feet are adjusted to the curvature of the lens until the axis of the collimator is parallel with the axis of the objective as defined by its outer spherical surface. The spot marking the centre of the plate is seen projected on the graticule, on which its position is read. The collimator is then placed at the opposite edge of the lens and another reading of the plate centre taken. Half the difference of the readings is the divergence of the axis of the objective from the centre of the plate. By means of the tilting screws they are made to coincide. To adjust the plate bearings the collimator is taken from its tripod and mounted at the centre of a plate of the same size as the photographic plate. The spot defining the centre of the objective is observed with the collimator placed on the plate bearings in the two positions 180° apart. As before, half the difference of the readings is the error of perpendicularity, which is corrected by moving the adjustable bearings. When these adjustments are satisfactory, the focus is determined from a photograph of a star field with several exposures made at small intervals of the focusing scale, the telescope being slightly displaced between the exposures. Perfect sharpness over the whole plate is not possible because of the unavoidable curvature of the

field, but uniform definition is secured by a compromise between the central and the lateral images.

In an object-glass of moderate dimensions the crown and flint lenses are permanently adjusted in a single cell by the maker, and once correct should never alter. With very large lenses this is not the case, the crown and flint being mounted in separate cells which are adjusted on the telescope. In any case the adjustment of lens should always be tested, and we will now proceed to do so.

The usual type of objective is composed of two lenses—a double convex crown-glass lens in front, and a plano-concave flint-glass lens behind. When in perfect adjustment the principal axes of both

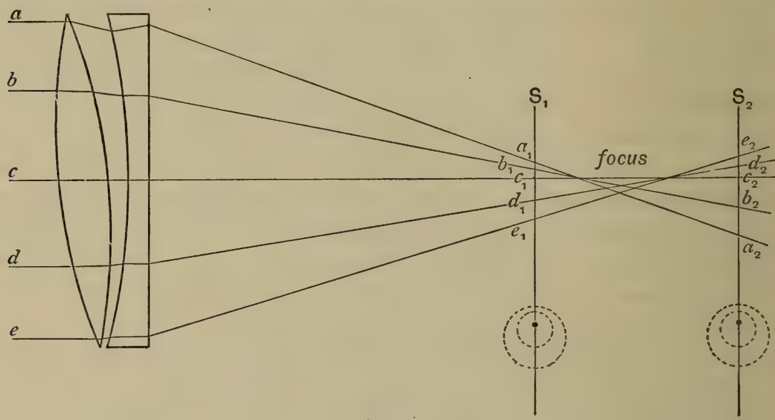


Fig. 1

lenses are coincident. If out of adjustment the crown may be tilted with respect to the flint, or it may be excentrically placed. When the error is large the optical distortion of the stellar image is very evident, but when small is only seen by examination of the extra-focal image. With perfect adjustment this is a disc composed of concentric rings or zones.

An error of tilt is indicated by an excentricity of the zonal rings.

A simple diagram (fig. 1) illustrates the optics, and shows that the zones condense on the side corresponding to the greatest separation between the lenses. Hence, to correct, push the crown in on the side on which the condensation lies.

The centring is tested in a similar manner.

In a simple lens the red rays are brought to a longer focus than the blue because of the greater refrangibility of the latter. In a flint-and-crown combination the colour-aberration is partially cor-

rected. Two rays of different wave-length on either side of an appropriate wave-length are brought to focus in the same plane—the plane of minimum focal length. All rays outside these limits will focus at a greater distance from the lens.

In a photographic telescope with a simple crown-and-flint combination the rays between approximately λ 4000 and λ 4800 focus in one plane; the ultra-violet and the red focusing beyond. One may consider the edge of the crown lens as a prism of a certain angle, whose dispersion is compensated by the edge of the flint lens—also a prism. If the crown lens is out of centre, suppose overlapping the flint, then the angle of the crown prism is smaller than that which the flint was calculated to correct, consequently there will be over-correction and the image will be distorted into a short spectrum with violet in the direction in which the crown is de-centred. If the error is large the colour can be readily seen and reduced. When the error has been made very small, photographs of the extra focal image will show a disc with concentric rings, if the tilt is correct, but with an excentric nucleus. This nucleus is the ultra-violet light which comes to focus outside the blue.

If a colour-sensitive plate is used, a red nucleus would be shown excentric in the opposite direction. To correct, therefore, the crown is to be pushed in the direction in which the violet nucleus is to be moved.

Measurement and Reduction of the Photographs.—In planning the astrographic chart the whole sky was subdivided into a number of fields or plates 2° square, spaced at definite intervals. For convenience in the subsequent work of reduction these centres were placed at 2° intervals along the even degrees of declination, and to duplicate the work a second series were placed at intermediate right ascensions along the odd degrees of declination, their centres coinciding with the corners of the first series, so that if a star were unfavourably situated on one plate it would be well placed on the overlapping plate.

A star suitable for guiding was selected, and its rectangular co-ordinates calculated with reference to the centre of the field. When the telescope was pointed to the right ascension and declination of the centre of the field and the eye-piece of the guiding telescope set, by means of the cross-slides, to the calculated co-ordinates, the star would be found under the eye-piece.

In the field of the eye-piece are two spider lines crossed at right angles. The observer places the star at the point of intersection

and keeps it there throughout the exposure. On the accuracy with which he guides, the quality of the photograph will largely depend.

After having secured the photograph, the plate must be measured in order to determine the positions of the stars shown on it.

As the position of a place on the earth is defined in terms of latitude and longitude, so the position of a star in the sky is defined by exactly similar co-ordinates—declination and right ascension. These, however, cannot be measured directly from the photograph. The fundamental property of the stellar photograph is that it is a projection of the celestial sphere from a point (the centre of the object-glass) on a tangent plane (the photographic plate). It follows then that any great circle of the sphere is projected as a straight line on the plate, and conversely every straight line on the plate corresponds to a great circle on the sphere. The appropriateness of using rectangular co-ordinates in the measurement and reduction of photographs is thus apparent.

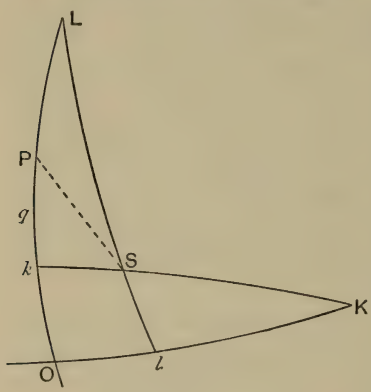


Fig. 2

Let O be the centre of the plate, K and L the poles of the great circles OL and OK on the celestial sphere, P the north pole of the heavens (fig. 2).

Let A and P be the Right Ascension and North Polar Distance of the centre O, a and p be the Right Ascension and North Polar Distance of any star S on the plate.

Then $PS = p$; $OP = P$; $OPS = a - A$,

$$\tan Ol = x \text{ co-ordinate of the star S,}$$
$$\tan Ok = y \text{ co-ordinate.}$$

$$\text{If } Pk = q, \quad \tan q = \tan p \cos(a - A),$$
$$Ok = P - q,$$
$$y = \tan(P - q); \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\tan Ol = \frac{\tan kS}{\cos(P - q)},$$
$$\tan kS = \tan(a - A) \sin q,$$
$$x = \tan Ol = \tan(a - A) \sin q \sec(P - q) \ldots (2)$$

By these formulæ right ascension and declination may be readily converted into rectangular co-ordinates, and by inversion right ascension and declination may be calculated from the measured co-ordinates. However, before these are converted into right ascension and declination they must be corrected for the " plate constants ".

These are: (1) Scale—due to the difference between the assumed and real focal length of the telescope. (2) Orientation—the twist of the plate. (3) Zero—the error of the pointing of the telescope.

On the plate will be found certain stars whose positions in right ascension and declination have already been determined with the meridian circle, and their rectangular co-ordinates are calculated by the above formulæ. These are called standard co-ordinates X, Y.

Comparison of these with the measured co-ordinates x, y, furnishes equations of the form:

$$ax + by + c = X - x,$$
$$dx + ey + f = Y - y.$$

It will be seen that three stars are sufficient to determine all the necessary constants for a plate. More, of course, are desirable, twenty if possible.

a and e are the corrections for scale, b and d those for orientation, whilst c and f are the zero corrections to the origin. The constants are applied to the measured co-ordinates of all the stars on the plate, and the corresponding right ascension and declination may then be calculated.[1]

The old astronomers essayed to observe with the greatest accuracy possible the positions of the brighter stars in the sky in terms of right ascension and declination. Continuous observation revealed the fact that the stars were not fixed, and from the observed motions the precession of the equinoxes, nutation, and aberration of light were determined.

Re-observation after a considerable period revealed yet another small motion, that proper to the star itself and hence called " proper motion ". For those stars which have been previously observed, the photograph supplies later positions from which their proper motion may be deduced.

The photograph, however, will contain many more stars than have been previously observed with the meridian circle or ever will be. Their exact positions in the sky are of little importance, but their

[1] Turner, *Astron. Society's Notices*, Nov., 1893.

proper motions, if any, are of great interest. If after an interval of years a second photograph of the field is taken and measured like the first, the measured co-ordinates may be directly compared by the formula $ax + by + c = x_1 - x_2$, &c., and stars having outstanding motions will show up in the residuals.

Measurement of the Photographs.—A measuring machine which is simple and accurate is described in the publications of the Yerkes and Allegheny Observatories. It consists essentially of a long and accurate screw which moves a microscope in a horizontal slide, the photographic plate being carried on a separate slide with motion in a direction perpendicular to the screw, so that stars of different y co-ordinates can be brought under the microscope. The image of a star is bisected on a wire in the microscope, and the x co-ordinate read off in terms of the screw. The plate is then turned through 90° and the y co-ordinate measured in a similar manner. Of course it is possible to move the plate also by a similar screw, when both co-ordinates may be measured at one setting.

It is clear that reliance must be placed on the accuracy of the slides and the constancy of the screw, and that, with a prolonged session, temperature effects from the proximity of the observer, &c., will be serious.

With photographs on which the stars are numerous and the measurement of the plate extends over hours, the last objection is fatal, so resort is made to the method of the *réseau* which, originally invented to check possible displacements in the photographic film, has since proved indispensable in the measurement of astrographic plates.

The *réseau* is a plate of worked glass covered with a silver film on which a network of fine straight lines has been ruled equally spaced in the x and y co-ordinates. The rulings are transparent, and the photograph, before development, is exposed behind the réseau for a short period to parallel light.

On development, together with the stars, a reticule of fine black lines is found printed on the plate, which is in this way divided into squares of convenient size—usually 5 mm.—and the position of the star in the square in which it appears is measured with an appropriate micrometer.

As it has been found that the photographic reproductions show differences from the silver réseau of the order of one micron, the réseau is not suitable for work of the highest precision. Short of this the method is excellent. The scale is constant, the zero per-

manent, so that, at any subsequent period, measures are readily verified or added to.

The lines are numbered in the direction of increasing right ascension and declination, and the co-ordinate of a star is expressed as the number of the line next before it and the fractional part of

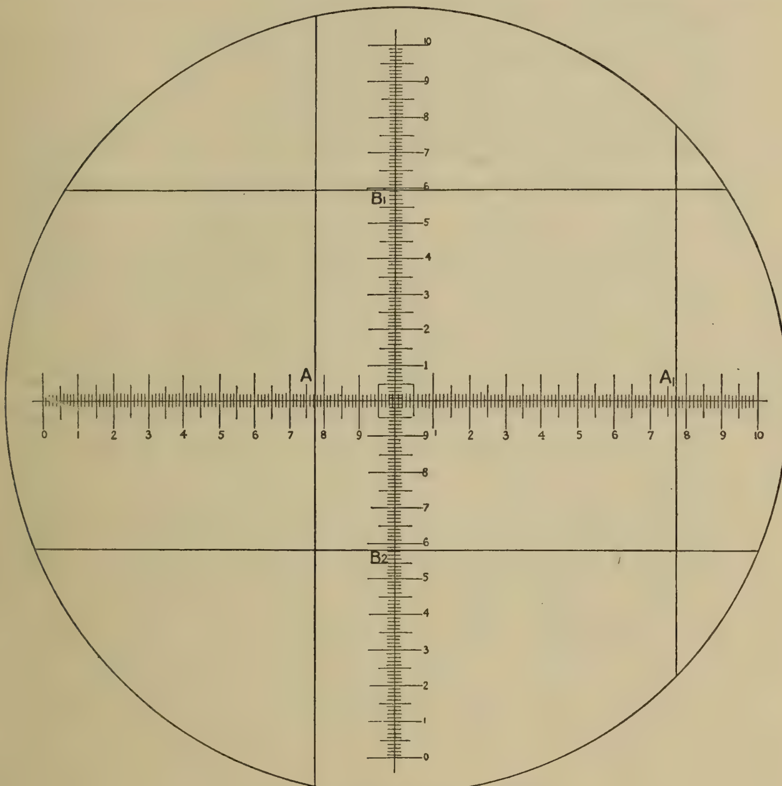


Fig. 3.—Diagram of Glass Diaphragm

the interval towards the next line, the second being measured under the microscope to the degree of accuracy required. Where considerable precision is desired a micrometer screw can be used, but in the work on the astrographic catalogue, where the mass of measurement was very great, the screw gave place to a method rather less precise, but much more rapid.

In the focus of the microscope a ruled-glass diaphragm is substituted for the spider line and screw. It has two scales crossed at

right angles, and so spaced that 100 divisions may be made to coincide exactly with a réseau interval. Each scale is 200 divisions in length, so that it is always crossed by two réseau lines. The divisions are numbered 0 to 100 from left to centre, and again 0 to 100 centre to right. The vertical scale is similarly numbered bottom to centre, centre to top. If a star is placed at the intersection of the scales, the distance from the line on the right is shown by the reading of the scale where the line intersects it; a similar reading will be found on the left. When the microscope is adjusted so that the image of the réseau fits the scale, the two readings will be the same, but if, as is usual, the fit is not exact a proportional part of the small difference has to be applied as a correction to the right-hand reading. Similarly in the y co-ordinate. In the astrographic work the réseau interval was 5 mm. The scale subdivided this into 100 parts, and the measurer would estimate to the tenth of a division, i.e. to one thousandth of an interval or one two-hundredth of a millimetre, which on the astrographic scale is three-tenths of a second of arc. Although this may seem somewhat rough, experience has proved that a mean of several measures gave all the accuracy required. Every star on the plate is measured and its position defined by its x and y co-ordinates.

It is often necessary to compare two photographs of a field of stars taken at different times, for example, photographs taken twenty years apart, for determination of proper motion. This may be done by measuring the co-ordinates of the stars on the two plates and making an algebraical adjustment as shown on a previous page. When the photographs are taken with different instruments there is no option, but if they are taken with the same telescope, comparison is better made without measuring the actual co-ordinates.

In the machine designed for this purpose the two plates are held side by side in a rigid frame mounted on a slide. They are viewed simultaneously by two microscopes mounted on a slide at right angles to the first, and the same distance apart as the plates. These are presumably taken at the same right ascension and declination, but may be adjusted for any small difference. When the left-hand microscope is pointed to a star on the left-hand plate the corresponding image on the right-hand plate will be found near the centre of the field of the right-hand microscope. Comparison is made by setting on the left-hand image and bisecting on the right. In this way the *differences* of the co-ordinates of the two stars are

obtained, adjustment again being made algebraically for setting and orientation by the formulæ

$$ax + by + c = x_1 - x_2,$$
$$dx + ey + f = y_1 - y_2.$$

In another form of this micrometer, by a system of prisms the images from the two microscopes are brought under the same ocular. Under the eye-piece is a reflector so arranged that the observer may bring the image from either microscope into the field of view at will. The image from the left (say) is reflected into the field and bisected by the micrometer wire, then by a turn of the reflector the image from the right is brought in and bisected, the difference giving the comparison required.

When a duplex micrometer is not available there is another method by which direct comparison may be made, and which gives good results. If in taking the second photograph the plate is reversed in the telescope and exposed through the glass, then, when the two photographs are placed film to film with the corresponding images in juxtaposition, and firmly clipped together, they may be treated as a single photograph with two exposures, and the displacement of the two sets of images can be measured under a single microscope.

Investigation has proved that, using ordinary glass, errors of the order of one micron may be expected but not more, whilst if the inverted plate is of " worked " glass and the measures are made through it they are quite negligible. They may be entirely eliminated if the inverted plate is used merely as an intermediary scale with which two or more photographs are successively compared. This is preferable, but naturally doubles the work of measurement. It has the advantage, however, that one is not restricted to the comparison of pairs of plates, but all may be compared together and each given its appropriate weight.

The measures, of course, will not be affected by the errors of the slides of the measuring machine, and the effect of temperature changes is eliminated, the two plates being in contact and equally affected.

Stellar Photometry.—The apparent brightness of a star is the first indication we have as to its size, or conversely, to its distance. Accurate measurement of its apparent magnitude, as it is termed, is therefore of great interest.

Estimates of stellar magnitudes made two thousand years ago appear in the *Almagest* of Ptolemy. In this work the stars are

divided into six classes or magnitudes, the first designating the brightest and the sixth the faintest stars visible to the naked eye—sensibly the scale employed at the present day. Later astronomers have recorded magnitudes on a scale more or less in accordance, and discussions of their estimates showed that they can generally be well represented by a logarithmic scale in which equal divisions will correspond to equal ratios of light. This seems to be the natural scale or that demanded by the construction of the eye. Pogson showed that a scale closely agreeing with that commonly employed in eye estimates might be obtained by using 0·4 for the logarithmic division corresponding to one magnitude of light ratio.

Thus the magnitude $m = \frac{\text{log light}}{0{\cdot}4}$, or the light ratio for one magnitude $= 2{\cdot}512$.

This is the scale now generally adopted. In 1879 Professor E. C. Pickering undertook to standardize the photometric observation of stars in which up to that time there had been no very systematic plan. With a photometer of his own design he observed the magnitudes of more than 4000 stars down to the sixth magnitude, comparing them directly with Polaris, whose magnitude he assumed as 2·0, and adopting Pogson's scale. After certain corrections to bring them into general accordance with Argelander's observations, he produced a standard scale of magnitudes which has since been extended to fainter stars. This was a visual scale. The advent of photography necessitated the provision of a standard scale of *photographic* magnitudes, as visual and photographic colour-sensitiveness is not the same.

In the spectral classification of stars—B, A, F, G, K—the colour progresses from blue to red. Pickering proposed that a photographic scale should be based on the known visual scale by giving to the white stars of class A and of the sixth magnitude, the same magnitude in both scales, thus providing a zero, whilst the light ratio should be the same in both scales. On this basis, when the visual magnitude and the spectral type are both known, the approximate photographic magnitude may be deduced by applying the following corrections called colour indices to the visual magnitudes.[1]

Spectral type	B	A	F	G	K	M
Colour index	− 0·24	0·00	+ 0·28	+ 0·56	+ 1·00	+ 1·35

This provided to a certain extent for the brighter stars. For fainter stars another scheme had to be devised. A number of stars were

[1] *Harvard Annals*, Vol. LXXX., p. 152.

selected near the North Pole, ranging from Polaris to the faintest observable, and their photographic magnitudes were determined by a variety of methods.

This furnished a magnitude scale and is called the North Polar Standard Sequence. To determine photographic magnitudes a plate is exposed for an equal time successively on the field of stars and on the polar sequence. The stars are represented on the photograph as small dots varying in diameter with the brightness of the star. The disc is, of course, spurious, and is accounted for by photographic spreading, light scattering, colour aberration, &c.

Although the image is not a clean-cut disc the diameter can be measured with considerable accuracy, and comparison with the polar sequence is made by measuring the diameters of both field and sequence stars, the magnitudes of the field stars being determined by comparison and interpolation.

The relation between diameter and magnitude can be expressed by the empirical formula

$$M = m + k\sqrt{d},$$

where d is the diameter and m and k are constants.

Over a range of three or four magnitudes the formula is fairly good, but should not be strained beyond. It is an empirical formula and should be treated as such. Four magnitudes is equivalent to a light ratio of 1 to 40. Beyond these limits the character of the image changes owing to optical limitations. The images of the bright stars are showing evidence of the secondary spectrum and those of the faint stars are not black, so that in both cases the discs are no longer well defined.

A more satisfactory way of dealing with faint stars, when the images are grey, is to use a comparison scale made in the telescope by exposing a plate to a star for a succession of exposures which increase in geometrical ratio.

The scale so formed will be a group of images of an intensity progressing by fractions of a magnitude. This scale is mounted in the microscope of the micrometer in the common focus of the objective and ocular, and by the rectangular motions of the plate-holder the star image is placed near the two images it most nearly resembles, and its magnitude estimated to a tenth of the scale unit.

Similar estimates of the sequence stars furnish a calibration of the scale from which the estimates are converted into magnitudes.

This is a simple method, but has the defect that the scale images

are not formed in the focus of the microscope by the microscope objective, and are therefore not of the same optical quality as the star images which are so formed.

A better method and one that has given very satisfactory results is to use a duplex microscope with two objectives, one directed to the photograph, the other to the scale. By a simple train of prisms they are brought under one ocular, and the scale and the images to be compared are ranged side by side.

In the sketch (fig. 4) S is the image of a star on the photograph, S*c* is the scale with which it is to be compared. The corresponding beams pass through the objectives O_1, O_2, the prisms

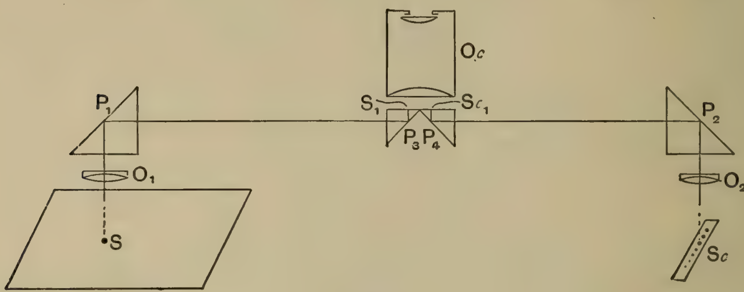


Fig. 4

P_1, P_2, and P_3, P_4 to the images S_1, Sc_1, and to the ocular O*c* with which they are viewed.

The *Extra-focal method* is perhaps more delicate, when the stars are sufficiently bright to permit of its application. Instead of exposing the plate at the focus, the telescope is racked in so that the plate intersects the cone of rays inside the focus, the star images appearing as large discs of varying density.

If the objective were perfect, spherically and chromatically, the light would be spread uniformly and the disc would be of even density. No objective, however, is perfect, and the disc has a more or less regular pattern. A method therefore has to be devised to diffuse this pattern, and one method is that used by Schwarzschild in which he made the image traverse a path crossing and recrossing, finally producing a uniform patch, the density of which varied with the brightness of the star.

The densities are compared in a microphotometer by means of a photographic wedge.

The Hartmann microphotometer—the apparatus usually em-

ployed for comparing densities—is in principle as follows. Two microscopes C and D have their axes at right angles, meeting on a Lummer cube—a cube formed by two right-angled isosceles prisms with their hypotenuse bases cemented together after a spot on one of them has been silvered. C points to the photographic plate, D to a photographic wedge, both of which are illuminated by mirrors R, R from the same light source I. The images of the plate and

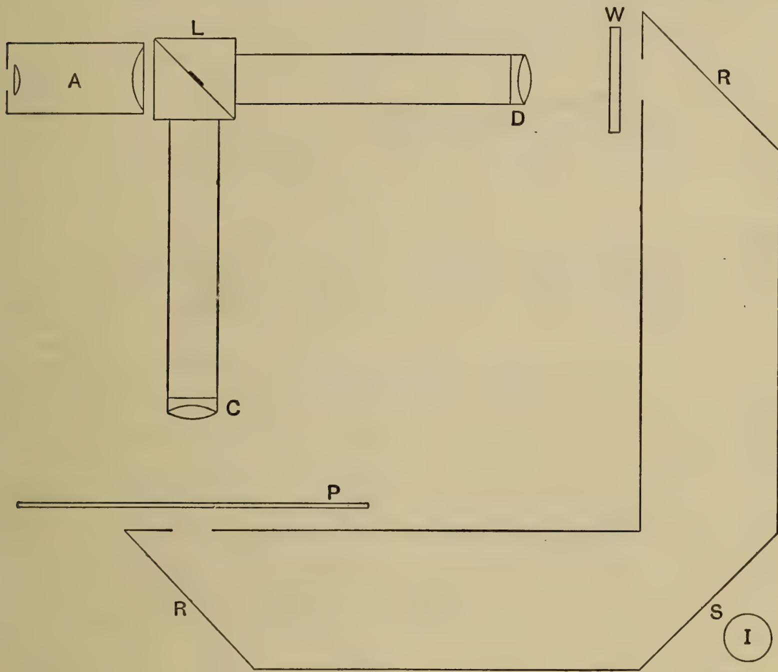


Fig. 5

of the wedge given by C and D are juxtaposed in the Lummer cube, that from the plate on the silvered spot, that from the wedge surrounding it.

They are viewed through the eye-piece A, and comparison is made by moving the wedge until the contrast between the images has disappeared.

Comparative magnitudes may be derived by comparison with the polar sequence as in the focal method, or they may be measured on an absolute scale by imprinting a light scale on the plate by exposing portions of it to a light source, the intensity of which is varied in

a known ratio, either by changing the size of the exposing apertures or by varying the distance of the light.

Absolute Light Scale. — The polar sequence, in the first instance, is assumed to be an absolute light scale; it is, however, only a close approximation, and much effort has been expended in checking and counterchecking the magnitudes of the stars of which it consists.

The inverse law, that equal photographic effect is produced when the light intensity and exposure time are varied in inverse ratio, i.e.

$$E = It,$$

is found not to hold in astrography.[1]

An expression approximately representing the facts is

$$E = It^p,$$

where the index p is a fraction which may vary from $\frac{6}{10}$ to nearly unity. An average value is about $\frac{9}{10}$, but the term is inconstant, and for that reason a light ratio cannot be determined from a time ratio.

Varying the aperture of the telescope is unsatisfactory as the aberrations at the centre and edge of the lens are not the same, and the images produced will not be of the same character; further, the selective absorption at the centre and edges will be quite different.

Wire-gauze screens placed over the objective are more promising, as, given the wire gauge and size of mesh, the absorption can be calculated. It will be necessary, however, to make two exposures, one *with* the screen and one unobstructed, and with prolonged exposures there are possibilities of a variation in the transparency of the sky.

The Diffraction Grating.—When a grating made of coarse parallel wires is placed before an objective, auxiliary images are produced in the focus on either side of a central image. A definite proportion of the light has been diverted into each of the lateral images, the proportion being a constant depending only on the dimensions of the elements of the grating, i.e. the width of the wires and of the space between the wires. There is thus a constant light ratio or magnitude interval between the central image of a star and the diffraction images on either side of it. There is this magnitude interval also between a given star and any other star whose central image is equal in size and density to the diffraction

[1] See p. 175.

images of the former star. Utilization of this fact provides a simple method for determining the magnitudes of all the stars on the plate (apart from a constant zero correction) when the magnitude interval of the grating is known.

The special advantage of the grating is that the auxiliary images are produced at the same time as the central images, the magnitude interval therefore being independent of the constancy of the transparency of the sky, an advantage not shared by any method which depends on an auxiliary exposure with the objective screened.

A disadvantage lies in the fact that the auxiliary images are really small spectra, slightly elongated, and consequently not strictly comparable with the round central images of fainter stars.

A second disadvantage is that the effective aperture of the telescope is diminished owing to the light stopped out by the opaque wires.

In designing a grating, then, the following points have to be considered.

1. Dispersion.
2. Absorption.
3. Magnitude interval.

1. If a is the width of the transparent space,
 d, the width of the opaque bar,
 f, the focal length of the telescope,
 D, the distance from the central to the first diffraction image,
 λ, the wave-length of the light,

all expressed in centimetres, then

$$D = \frac{f\lambda}{a + d}.$$

If the part of the spectrum which acts on the plate ranges from λ_1 to λ_2, the elongation of the image will be

$$\frac{f(\lambda_1 - \lambda_2)}{a + d}.$$

To diminish this elongation we must diminish $\frac{f}{a + d}$, i.e. we must choose such a pitch $(a + d)$ as will make the central and diffraction images as close together as possible; they must, however, be distinct.

The pitch must be as great as the size of the images given by the telescope will permit.

2. The *absorption*, the difference in brightness between the central image, using the grating, and the image obtained with an equal exposure without the grating, is expressed by the ratio $B_o : B = \left(\frac{a}{a+d}\right)^2$.

The effective loss therefore varies as the square of the ratio of the original and the obstructed apertures.

The bars must then be kept as narrow as the other requirements will permit.

3. *The Magnitude Interval.*

If B_m is the brightness of the mth lateral image,
B_o, that of the central image,

$$\text{Then } B_o : B_m = \left(\frac{am\pi}{a+d}\right)^2 \Big/ \sin^2\left(\frac{am\pi}{a+d}\right).$$

$$\text{In magnitudes } = 2{\cdot}5 \log\left(\frac{am\pi}{a+d}\right)^2 \Big/ \sin^2\left(\frac{am\pi}{a+d}\right)$$

$$= 5\left(\log\frac{am\pi}{a+d} - \log\sin\frac{am\pi}{a+d}\right).$$

Thus the magnitude interval like the absorption depends on the ratio of the transparent space to the opaque bar.

The following table may be useful in determining the value of $\frac{a}{a+d}$ to give a required magnitude interval.

$\frac{a}{a+d}$.	$\frac{d}{a+d}$.	Magnitude Interval.	Absorption in Magnitudes.
0·950	0·050	6·402	0·111
0·900	0·100	4·806	0·229
0·850	0·150	3·848	0·353
0·800	0·200	3·155	0·484
0·750	0·250	2·614	0·624
0·700	0·300	2·171	0·774
0·650	0·350	1·800	0·936
0·600	0·400	1·486	1·109
0·550	0·450	1·214	1·298
0·500	0·500	0·980	1·505

A magnitude interval of about 3 magnitudes has been found most generally useful. If the interval is much greater the number of stars on the plate showing diffraction images will be small, and further the ratio $\frac{d}{a + d}$ will need determining with very great accuracy.

On the other hand, if the interval is much smaller the loss of light is excessive, and if used to check a sequence there will be an accumulation of error from the number of " steps " involved.

As a practical illustration, take two gratings used at Greenwich for checking the polar sequence.

	Grating I.	Grating II.
Diameter of wires (d) ..	0·693 mm.	1·717 mm.
Pitch ($a + d$)	5·000 ,,	7·000 ,,
Magnitude interval ..	4·036 mags.	2·660 mags.
Absorption	0·325 ,,	0·610 ,,

With the telescope employed, of focal length 6837 mm., the effective photographic light extends from λ 4100 tm. to λ 4900 tm., with a mean for the average star of λ 4500 tm.

The dispersion D is then 0·62 mm. and 0·45 mm., and the elongation for 800 tm. 0·11 mm. and 0·08 mm. Without the grating the diameter of a small black star image is about 0·07 mm.

Therefore, as was actually the case, the images with grating I would be slightly elongated and a better result would have been achieved with a larger pitch, whilst those with grating II were sensibly round and comparable with the central images of fainter stars.[1]

Stellar Parallax.—A surveyor, wishing to measure the distance to an inaccessible point—a church spire, for example, on the farther side of an impassable river—solves the problem by measuring a base line along the bank, and then from either end observing the angles between the spire and the opposite end of the base. The distance is then calculated by simple trigonometry. Whilst walking along his base line he would probably have noticed that the church spire appeared to change its position against the more distant background, a large amount if near, and less in proportion to its distance.

The determination of the distance of a star is a similar problem

[1] Chapman and Melotte, *Monthly Notices R.A.S.*, Nov., 1913

and is solved in a similar manner—by observing its motion against the background of fainter and presumably more distant stars.

In the course of a year the earth travels through a nearly circular orbit. Hence after a lapse of 6 months it finds itself at a point one diameter or 186 million miles from where it was previously. The near stars should therefore suffer a displacement relatively to the distant stars.

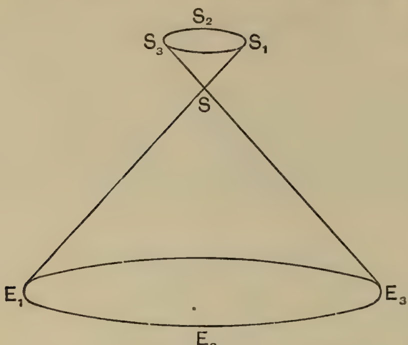


Fig. 6

When the earth is at E_1 (fig. 6) the star S appears at S_1, and when the earth is at E_2, E_3, the star appears at S_2, S_3. As the earth moves through its orbit the star would appear to trace a path in the sky similar in shape and equal in size to the projection of the earth's orbit as seen from the star. If then the angle E_1SE_3 can be measured, the distance E_1S can be determined in terms of the radius of the earth's orbit. Half the angle E_1SE_3, or that subtended by the radius of the earth's orbit, is called the star's parallax.

Earlier astronomers, like the surveyor, attempted to determine absolute distance by measuring the large angles at the base of the triangle, being unaware of the immensity of the scale of the universe, and the corresponding minuteness of the parallactic angle of even the nearest star — so small as to be lost in the unavoidable errors of observation. Realizing this, Herschel fell back on the plan of determining *relative* distances by measuring the displacement of bright stars relatively to faint and presumably more distant stars. This is essentially the method employed at the present day.

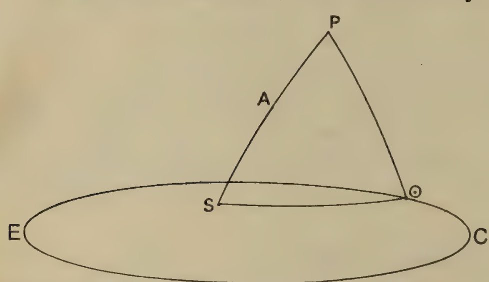


Fig. 7

As the earth moves in its orbit the star will trace out a corresponding ellipse on the celestial sphere. At any instant the star will be displaced from its true position by an amount proportional

to the radius of the earth's orbit foreshortened by the sine of the angular distance between the sun and the star.

EC is the ecliptic;

P, the celestial pole;

$\odot$ the position of the sun in the ecliptic at any instant;

S the mean position of the star.

The star S will trace out an ellipse similar to EC, on the celestial sphere and its displacement at a given instant will be proportional to R sinS$\odot$, R being the radius of the earth's orbit, and S$\odot$ the angular distance between the sun and star.

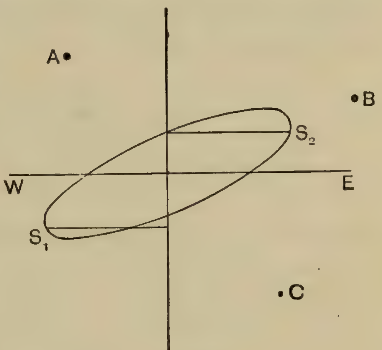


Fig. 8

Although the total displacement S$\odot$ may be measured, it is more convenient to work in right ascension and declination into which it is resolved.

Then if π is the parallax, i.e. the angle subtended by the semi axis major of the ellipse, and f is the proportional part observed,

$$
\begin{aligned}
f\pi &= \text{R sinS}\odot, \\
f\pi_\alpha &= \text{R sinS}\odot \text{ sin PS}\odot \\
&= \text{R sinP sin P}\odot \\
&= \text{R sin}(\odot\text{'s RA} - \text{star's RA}) \cos\odot\text{'s dec.} \\
f\pi_\delta &= \text{R sinS}\odot \text{ cos PS}\odot,
\end{aligned}
$$

but this part being usually much smaller than the RA component is, in practice, neglected.

The parallax factor in right ascension is greatest therefore when the star is 90° or 6 hours before or after the sun, i.e. when the star transits at 6 a.m. or 6 p.m., the displacement being positive in the morning and negative in the evening. These are the times at which the necessary observations are made.

To determine the parallax of a star then, photographs are taken at intervals of 6 months, when it is nearly 90° east or west of the sun.

In the first case it would appear in the position S_1 and in the second at S_2. The displacement in right ascension from S_1 to S_2 is measured by reference to faint stars in the neighbourhood. A, B, and C, for example, are stars relatively distant. On the first photograph the position of S_1 in the x co-ordinate (or right ascension) is measured

relatively to the comparison stars; on the second photograph S_2 is similarly measured, and the difference $x_1 - x_2$ is the displacement in right ascension in the interval. As this displacement contains the star's proper motion as well as the parallax, observations at two epochs only are insufficient. Three epochs at least are necessary and more are desirable.

After measurement and reduction to a common system the x co-ordinates of the parallax star as derived from the photographs are equated to the form

$$\begin{aligned} f_1\pi + t_1\mu + c &= x_1, \\ f_2\pi + t_2\mu + c &= x_2, \\ f_3\pi + t_3\mu + c &= x_3, \\ \&c. \qquad &= \&c., \end{aligned}$$

where π is the star's parallax and f its computed factor, μ is the proper motion, and t the time of observation in years. A solution by the method of least squares will give the values of π and μ.

The procedure is perfectly simple, but the quantity sought is so minute that no possible refinement may be neglected. Thus special care must be taken over the constancy of the optical adjustments of the telescope. The plates must be taken at the same hour angle to eliminate errors due to atmospheric dispersion and possible flexure in the large lenses, and the guiding must be exact. To eliminate the residuals of all these possible errors, only stars of the same magnitude should be compared, and if possible only those of the same colour.

As the star under examination is usually bright, in order to compare it with the faint stars in the background, its light has to be reduced by some contrivance such as a neutral-tinted filter or an adjustable shutter.

The usual device is the revolving sector shutter consisting of a disc made in two parts, which may be adjusted to leave a sector opening of a width suitable for reducing the light of the star to the required brightness. The star is brought under the disc, which is rotated by clock-work or electric-motor, exposing the star intermittently through the sector opening, the faint comparison stars being meanwhile exposed continuously beyond the disc. Finally, care must be taken in the development and drying of the plate, which should be uniform, or film-displacement may occur.

In photography of precision the gelatine film has always been regarded with suspicion—to a large extent without justification.

To avoid the errors supposed to be due to this, a method of observing parallaxes was proposed by Professor Kapteyn, wherein the same plate was exposed at three successive epochs, six months apart, morning, evening, morning; or evening, morning, evening; and then developed. Comparison of the second exposure with the first and third gave the parallactic displacement, whilst comparison of the first and third gave the proper motion. Theoretically perfect, the method, after a thorough trial, has had to give place to single-epoch plates on account of climatic difficulties, a good first epoch being often spoilt by a poor second epoch.

Measurement of the Plates.—In dealing with the Kapteyn plates it was only necessary to measure in the microscope with the micrometer screw the differences in the x co-ordinate (or right ascension) of the morning and evening images for the comparison stars and the parallax star. These were equated by the linear formula $ax + by + c = \delta x$, and when the difference for the parallax star had been corrected for the derived constants, a residual remained which is made up of proper motion (μ) and parallax (π).

A Kapteyn plate will thus yield an equation:

$$f_1\pi + t_1\mu = R_1,$$

$$\text{or} \quad f_2\pi - t_2\mu = R_2,$$

where t is the time elapsed between the exposures and f is the difference (morning — evening) of the parallax factors.

Single-epoch plates must be measured against a scale. This may be either a graduated scale with which the photograph is compared in a projection micrometer or, as some prefer, a long accurate screw which moves the microscope across the plate and with which the pointings on the star images are made, the measures being read on a large graduated head.

Parallaxes derived in this manner are "relative" to the comparison stars. By applying a small correction equal to the average parallax of the comparison stars, they are made absolute.

Discussion of the proper motions of stars show that there is a general drift from a point in the heavens at right ascension 18 hours and north declination 30°. From spectroscopic observations of the motions of stars in the line of sight it is found that the rate at which the sun is moving towards this point is 20 Km. a second or 4 solar units in one year.

Had the stars no individual motion, the apparent proper motion would be a true parallactic motion and a criterion as to distance,

but the stars have individual motions as great or greater than that of the sun, so that the criterion only holds in the average. It is, however, possible to make an estimate of the *average* distance of stars, given the magnitude. Thus stars of the 10th magnitude are assumed to have an average parallax of $+0\overset{''}{.}004$, and of the 11th magnitude a parallax of $+0\overset{''}{.}003$. If then the comparison stars are of 11th magnitude, a correction of $+0\overset{''}{.}003$ is applied to the relative parallax, and the corrected result is presumed to be the absolute parallax.

The Reflecting Telescope.—Despairing of a solution to the problem of the achromatism of the telescope objective, Newton turned his attention to the possibilities of the concave mirror and actually constructed a small telescope on this principle. Later under Herschel's skilful hands the reflecting telescope rose to high esteem.

The great advantages of the speculum reflector were:

Simplicity of construction,
Perfect achromatism.

Against this had to be set:

Its weight and the consequent difficulty of holding it rigidly without straining its figure,
Sensitiveness to temperature changes,
Its surface could not be kept in high condition without the attention of a skilled optician.

The discovery and perfection of methods of depositing a silver film on glass have now made it possible to use, instead of the weighty metal speculum, a glass mirror silvered on its optically figured surface. This silver film takes a very high polish, and when tarnished the mirror can easily be resilvered by any intelligent person.

Whilst, because of its greater robustness and stability, the perfected refracting telescope can never be supplanted by the reflecting telescope for fundamental observations of position, yet there is a very wide field in which the reflector is the superior, particularly in the realm of spectroscopy.

Its perfect freedom from chromatic aberration is a matter of the first importance in astrophysical work. With a refracting telescope only a short range of the spectrum focuses in one plane. In the 36-in. Lick telescope, for example, the focus for H_δ is 81 mm. beyond that for D. A star focused on the slit in D light would

be considerably out of focus in H_δ light, with a consequent diminution in the intensity of the spectrum at that wave-length. The resulting photograph would not give a true representation of the distribution of light throughout the spectrum.

The reflector has relatively small absorption for large apertures. In an object-glass composed of two lenses light is lost by reflection at four surfaces. The nature and amount of absorption depend on the quality of the glass used, but in all cases the most marked effect is in the ultra-violet. As a consequence it is impossible with the ordinary photographic objective to photograph any considerable part of the ultra-violet spectrum of a star. The reflector on the other hand serves admirably in photographing the shortest wave-lengths that penetrate our atmosphere.

On the assumption that 50 per cent of the chemically-active rays (λ 4300) reach the focus of a Newtonian reflector, it has been shown that whilst for small apertures the refractor is the more efficient, yet as the aperture is increased the absorption due to the increased thickness of the lenses ultimately extinguishes this advantage.

The following table gives a comparison of the light-grasping power for the chemical rays of the refractor and the reflector for different apertures.[1]

	Light-grasping Power.	
Aperture.	Refractor.	Reflector.
11 inches	5·41	3·76
22 ,,	18·19	15·05
33 ,,	34·57	33·89
44 ,,	51·43	60·21
55 ,,	68·60	94·08
66 ,,	81·85	135·48

It will be seen that at 33 in. aperture the reflector is as efficient as the refractor, whilst for such apertures as the Mount Wilson 60-in. and 100-in., and the Columbia 72-in., the reflector efficiency exceeds that of any possible refractor.

The mirror can also be made of relatively short focus—the usual ratio at the present day is 1 to $4\frac{1}{2}$. When this is compared with the photographic telescope with its ratio of 1 to 10, it is obvious how much greater is the concentrating power of the reflector, and hence its suitability for the photographic observation of faint and difficult objects.

The comparison of the relative efficiency of the refractor and

[1] Hale, *Astrophys. Journal,* Vol. V, p. 119

reflector applies to the Newtonian form where there are two reflections. It is possible to avoid the loss at the second reflection by placing the photographic plate directly in the focus of the large mirror as in the case of the 30-in. reflector at Greenwich. As with the astrographic telescope, guiding is effected with a supplementary telescope bracketed to the tube of the reflector. An objection to this plan is the possibility of a movement of the large mirror during a prolonged exposure resulting in a distortion of the photographed image. This difficulty has been surmounted by attention to the supports of the mirror, but as this latter is very sensitive to any constraint, a different method of guiding is preferred by American astronomers, and is probably essential to the highest performance of very large mirrors. By second reflection from a plane mirror the light from the large mirror is sent to focus at the side of the tube, where it is received on the photographic plate. The plate-holder is carried on cross-slides with fine motions in right ascension and declination. A limited strip of the field of the reflector, beyond the plate, can be viewed with an eye-piece, and when a suitable guiding star has been selected, the eye-piece with its cross wires is set on it and clamped. Throughout the exposure the guiding star is kept on the cross wires by the slow motions of the cross-slides of the plate-holder. Any movement of the mirror is thus corrected.

In photographing excessively faint objects a prolonged exposure is necessary. Beyond careful guiding, nebulæ and faint stars present no difficulty, but if the object is in motion, as, for example, a comet, minor planet, or one of the faint satellites of Jupiter, the faint trail on the plate would fail to register. Consequently the moving object must be made stationary relatively to the plate, the stars being allowed to trail. It is not practicable to guide directly on the object; it is either too faint or too ill defined. The rate and direction of motion are calculated and set off in a reversed direction at convenient intervals on a position micrometer fitted to the guiding eye-piece. If the guiding star is kept on the moving wires the plate will keep pace with the moving object, which will appear undistorted on the photograph, whilst the stars will be represented as trails.

Use is made of the planetary motion in an interesting method employed by Max Wolf at Heidelberg for detecting new minor planets. On a single photograph a minor planet is not easily distinguishable from a faint star, but if two photographs are taken of the same area, the second a short time after the first, on the second the

planet will have moved slightly from its position on the first. When the two photographs are viewed simultaneously in the stereoscope, the displacement between the two images is translated into the third dimension, and the planet is seen suspended in a plane above that of the stellar background.

The Photoheliograph.—A casual examination of the sun in a telescope reveals the fact that the luminous disc is not uniformly bright, but is broken by dark marks or spots, to the patient and systematic study of which we owe our knowledge of the movement of the sun on its axis and much of its physical character.

Before the introduction of photography the methods of observing the position of spots on the sun's disc may be thus described. If a telescope is pointed at the sun an image will be formed in its focus. With a low-power eye-piece this image is magnified and projected on a white screen. If in the focus of the telescope two wires are inserted, at right angles to each other and at 45° to the direction of diurnal motion, then when the telescope is firmly clamped the enlarged image of the sun will transit across the screen and the wires projected on it. If the six times are noted at which these wires are met by the edge of the disc and the centre of the spot, a short calculation will give the position of the spot, referred to the sun's centre.

The photoheliograph embodies this simple method of projection, the enlarged image being instantaneously recorded on a photographic plate.

In the instrument used at Greenwich, a small telescope 4 in. in aperture and 60 in. focus forms an image $\frac{6}{10}$ in. diameter at the principal focus, where also the spider lines set at right angles are placed.

An enlarging lens projects an image 8 in. in diameter on the photographic plate in the secondary focus. Exposure is made by causing a narrow slit rapidly to traverse the image in the principal focus.

The crossed wires on the photograph are used to determine the line of orientation. The inclination of the wires to this line is found by making two exposures on one plate—after stopping the clock-work—at such an interval as will cause the two images to overlap. The line joining the cusps—after correction for the sun's motion in declination—will give the north and south line.

Measurement of the photograph is made in a suitable micrometer in which the position angle of the spot and its distance from the centre of the disc may be directly measured. In the low-

power microscope used for the purpose there is also a diaphragm scale ruled into tiny squares, each representing approximately one five-hundred-thousandth of the projected area of the sun's disc, and the area of the spot surface is estimated in this unit. From these measures the longitude and latitude and the area of the spot may be calculated.

The periodic character of the amount of spotted area or of "solar activity" was announced by Schwabe in 1843. At a given date the sun may be nearly free from spots; very soon spots begin to appear, increasing in numbers until a maximum is reached, after which the activity gradually declines to another minimum, the period being about eleven years. Successive cycles are not identical in character, but an average of a large number of observed cycles gives a mean period of $11\frac{1}{9}$ years.

A peculiarity of the phenomenon is that the outbreak occurs in high latitudes of 35° or thereabouts. As the cycle progresses the spot zones move in towards the equator, maximum activity being in about latitude 15°, the cycle finally dying out near latitude 6°.

Observations of the movement of spots across the sun's disc give data for determining the period of rotation and direction of its axis, and as some spots persist for two or even more rotations it might be thought that this period could be quickly and accurately determined. This, however, is not the case, as different spots give different periods. The fact is, the sun is not a solid body and has no single period of rotation, the outer layers drifting around at a rate varying with the latitude. At the equator the period is a little less than 25 days, whilst in latitude 50° it is about $27\frac{1}{2}$ days.

In the neighbourhood of the dark spots a good photograph shows bright markings called faculæ. These are seen at their best near the edge of the disc, where the contrast with the photosphere is enhanced by the absorption of the sun's atmosphere.

There is another feature—the texture or granulation of the photospheric surface which on photographs of fine definition appears as a fine mottling. It is attributed to very local convection currents in the lower atmosphere, the bright marking being the crest of the rising coloumn, the darker divisions the cooler descending gas.

Photographs of Star-trails for determining the constant of aberration and the variation of latitude. A person walking through a shower of rain which is falling vertically, no matter in what direction he moves, will always feel the rain beating in his face. The apparent direction of the rain is the composition of its own direction and

velocity with that of the observer. Thus if in a given interval the rain fell vertically from C to B whilst the observer moved from A to B, the rain would appear to fall in the direction CA.

Light having a finite though great velocity and the earth a certain though relatively small velocity in its orbit, a precisely similar deflection takes place when observing the direction of the heavenly bodies; there is a small displacement towards that point towards which the earth is moving; greatest when the direction of the body is at right angles to the line of the earth's motion, and diminishing in the ratio of the sine of the angle between the line joining the star and the direction of the earth's motion.

In consequence of this, as the earth travels round the sun any star appears to trace out a small orbit which is a projection of the earth's orbit as seen from the direction of the star—circular at the poles of the ecliptic, a line in its plane, and an ellipse at intermediate latitudes. The angle subtended by half the major axis of the ellipse is called the constant of aberration, and is 20·″5 very nearly. The displacement in longitude is greatest when the star is in line with the earth and the sun, or when the star transits at midday or midnight. It is greatest in latitude when the star transits 6 hours before or after midday, positive in the evening, and negative in the morning.

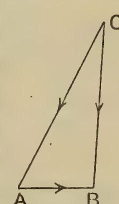


Fig. 9

We have already seen that a star at a measurable distance will trace out an ellipse on the sky. Here, however, the greatest displacement in longitude occurs when the star transits 6 hours before or after the sun, and in latitude when it transits at midday or midnight, which is exactly the reverse of the aberration ellipse. Bradley, in 1725, attempted to determine the parallax of γ Draconis by continuous observation of its declination throughout the year. He discovered a movement, but one not corresponding to a parallactic motion, and which he ultimately correctly interpreted as due to the aberration of light.

As by means of the spirit-level and mercury-trough the direction of the zenith can be very accurately determined, the observation of zenith distances of stars affords a ready method of determining its constant.

For a still more precise determination a floating zenith telescope was constructed in 1901 by Mr. Bryan Cookson.[1] As the instru-

[1] Monthly notices, R.A.S., March, 1901.

ment has been employed with great success a brief description is given here.

The instrument is comprised of three principal parts—the trough, the float, and the telescope. The trough and float are shallow annular basins; the float is concentric with the trough and fits inside with half an inch clearance all round. Mercury is poured into the trough, and the float is free to take up its position of equilibrium in the bath of mercury.

The telescope passes through the centre of the annulus, and its trunnions rest in V's which are carried by the float. The trough is fixed, but the float is free, and can be rotated in azimuth. The trough is supported by three pairs of iron rods at a height of $4\frac{1}{2}$ ft. from the floor to permit of manipulation at the breech end of the telescope. The inside diameter of the trough permits the telescope being moved to a maximum zenith distance of 45°. The telescope has an object-glass of $6\frac{1}{2}$ in. aperture and 65 in. focal length. The scale is approximately 1 mm. = 30″.

The instrument is used for photographing the trails of stars across the meridian. By turning the float in the circular trough and always bringing two points on it opposite to two fixed points on the trough, the float can be rotated through exactly 180°. It follows then that as the axis of rotation is vertical, the line of intersection of the plane of the meridian with the plane of the photographic plate is the same line before and after rotation. The position of the meridian on the photographic plate is indicated by the silhouette of a copper wire stretched across the breech of the telescope from north to south immediately in front of the plate.

If now a star very near the zenith is allowed to trail across the plate until it has nearly reached the meridian, and the telescope is then rotated through 180° and the same star trailed just after passing the meridian, on development of the plate the two trails will appear on the same side of the meridian line but separated by a distance equal to twice the zenith distance of the star. To determine the aberration constant, it should only be necessary to follow some suitable star through the year, observing the variations in its zenith distance as it traced out its aberrational ellipse.

There is, however, a complication introduced by a recently discovered motion of the earth known as the variation of latitude. The motion of the earth's axis relatively to the heavens, called nutation, has long been known, but the variation of latitude is a change of direction of the earth's axis within itself, giving rise to a

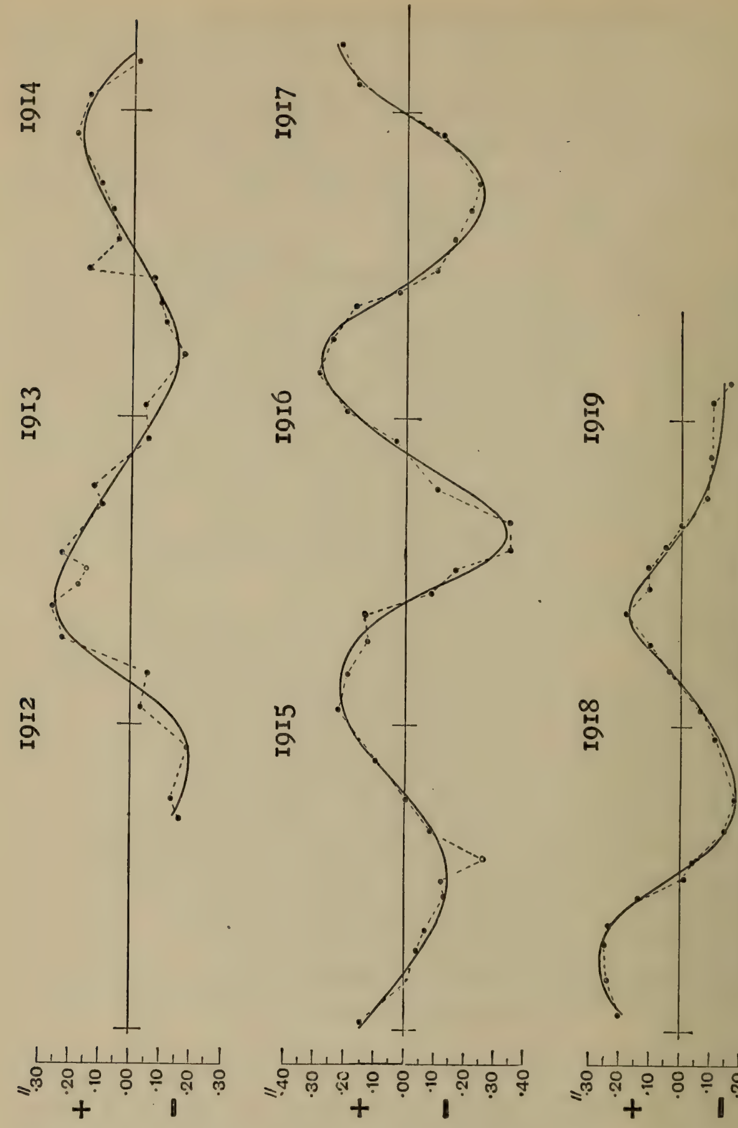
change in the latitude of a given point on the earth. The motion of the pole is an irregular one, with two known periods, one of 12 months and one of 14 months, which so combine that the latitude variation is sometimes smaller and sometimes larger, but at its greatest scarcely exceeds half a second of arc. Expressed popularly, the earth's pole traces out a sort of spiral path, the track being confined within the limits of a tennis-court.

In the observation of a single star, aberration and the annual term of the latitude variation are hopelessly confused. It will be recalled, however, that whilst the latitude is unchanged throughout the night, the aberration is varying from hour to hour. If two stars are selected 6 hours apart, and the first transits at 6 p.m., its zenith distance will be affected by the latitude variation and a large aberrational displacement, whilst the second star, transitting at midnight, will still be affected by latitude variation but no aberration. The two quantities may then be disentangled by observing four stars at 6-hour intervals cyclically throughout the year. From these a set of equations are derived from which both aberration and latitude variation may be determined.

So far only observation of stars near the zenith has been considered. There is, however, a serious disadvantage in confining oneself to these, as suitable stars in sufficient number can only be found at some little distance from the zenith, which means that the distance measured on the plate is considerable—amounting to 2° or more. The quantity sought is only a small fraction of a second or arc, and it is unsound in principle to attempt to determine very small quantities from the differences of very large quantities which are subject to errors arising from change of scale, &c. The first observations made with this instrument, using zenith stars, were only moderately successful for this reason.

With the experience gained another method was adopted when the instrument was set up at Greenwich—the method of "Talcott pairs".

A single zenith star is replaced by two of nearly equal distance north and south of the zenith. The pair are chosen a few minutes apart in right ascension, giving time for the reversal and steadying of the telescope between them. Setting the telescope to the zenith distance of the first star it is allowed to trail right across the meridian. Without altering the zenith setting, the telescope is then reversed by rotating the float through 180°, and in due time the second star trails across the plate. The two trails will be found running parallel



LATITUDE VARIATION AT GREENWICH (Mean *minus* observed latitudes)

Fig. 10

across the meridian line, separated by twice the mean (algebraic) zenith distance of the two stars.

It is evident that the observation will be strengthened by using a group of stars instead of a single pair, so for practical reasons the simple programme of 4 pairs of stars was not adhered to. Instead,

an enlarged programme consisting of 16 groups, each group containing 4 or 5 pairs of stars and extending over about 1 hour of right ascension, was adopted. Each group is photographed on one plate. The groups were observed as near 6 a.m. and 6 p.m. as possible, and in cyclical order to eliminate the errors of the star places.

The measurement of the photographs is extremely simple. The pairs were selected so that the mean zenith distance was small, and the quantity to be measured is the distance, not exceeding 7 mm. or 14 minutes of arc between two parallel trails.

The micrometer is one of the projection type in which the plate is carried in a slide capable of a perpendicular motion. Two microscopes are carried on a rigid bar capable of horizontal motion. The plate is viewed through the left-hand microscope whilst a divided scale is viewed through the right-hand. Any length on the plate can therefore be projected on the scale. A setting is made on one of the trails in the right-hand, and with a micrometer a division of the scale is bisected in the left. The microscope is then moved to the second trail, on which a setting is made, and a corresponding bisection made on the scale.

The reduction of the measures and the formation and solution of the normal equations cannot be given here. The results of seven years' observations from 1911 to 1919, however, are of interest. The deduced correction to the constant of aberration is

$$-0.''025 \pm 0.''009.$$

The latitude variation results over the same period are given in the table on the following page, and are shown graphically in the accompanying diagram (fig. 10).

It is concluded from these results that the floating zenith telescope will give an accurate determination of latitude variation, and that accumulated observations will in time give a determination of the aberration constant of a high order of accuracy.

Spectrum Analysis and Astrophysics.—In Newton's historical experiment, a pencil of sunlight admitted through a round hole in the shutter of a darkened room was caused to pass through a glass prism and to fall on a screen. He thus obtained what he called a spectrum, that is an orderly arrangement of a series of coloured images of the hole in the shutter, these coloured images appearing in different positions by virtue of the different amount of refraction suffered by rays of different colours. The spectrum he obtained was necessarily very impure on account of the overlapping

Latitude Variation at Greenwich, 1911·7 to 1919·1

Date.	Lat. Var.	Date.	Lat. Var.
1911·70	− 0·″140	1915·44	− 0·″083
·77	− 0·116	·51	− 0·142
·94	− 0·207	·58	− 0·336
1912·06	− 0·023	·66	− 0·337
·18	− 0·070	·77	− 0·089
·27	+ 0·227	·91	+ 0·012
·37	+ 0·257	1916·04	+ 0·211
·44	+ 0·175	·17	+ 0·270
·48	+ 0·154	·27	+ 0·237
·54	+ 0·220	·37	+ 0·170
·68	+ 0·104	·42	+ 0·059
·76	+ 0·126	·50	− 0·106
·94	− 0·062	·58	− 0·157
1913·03	− 0·054	·69	− 0·201
·20	− 0·191	·77	− 0·247
·30	− 0·109	·92	− 0·130
·36	− 0·094	1917·07	+ 0·178
·45	− 0·063	·18	+ 0·222
·49	+ 0·122	·29	+ 0·244
·58	+ 0·044	·35	+ 0·233
·67	+ 0·058	·44	+ 0·130
·76	+ 0·116	·50	− 0·023
·92	+ 0·194	·54	− 0·035
1914·04	+ 0·142	·66	− 0·149
·17	− 0·024	·76	− 0·184
·29	− 0·049	·94	− 0·155
·35	− 0·077	1918·06	− 0·054
·45	− 0·138	·19	+ 0·068
·49	− 0·132	·27	+ 0·102
·57	− 0·264	·36	+ 0·191
·65	− 0·091	·43	+ 0·099
·74	− 0·008	·50	+ 0·105
·91	+ 0·109	·57	+ 0·058
1915·06	+ 0·234	·66	+ 0·012
·17	+ 0·191	·74	− 0·071
·27	+ 0·119	·90	− 0·084
·35	+ 0·114	1919·06	− 0·106

of the adjacent images. On consideration it would have been apparent that a purer spectrum would have resulted by replacing the hole with a narrow slit transverse to the length of the spectrum, and this was actually done by Wollaston in 1802, though as the result of an accident and not by deduction. With this improvement he

noticed that certain dark lines crossed the spectrum, but he appears to have gone no further.

Fraunhofer further improved the apparatus for studying the spectrum by interposing a convex lens between the slit and the prism, instead of allowing the rays to pass directly through the prism. He thus projected images of the slit on the screen, obtaining a well-defined spectrum in which the black lines were well marked. To the study of the phenomena of these black lines to which his name has been given, Fraunhofer devoted much labour. He showed that they had perfectly fixed positions in the solar spectrum, and mapped about 700 of them. The eight chief and most decided of them he labelled with the letters of the alphabet, beginning in the red at A and ending in the violet at H.

He also invented and constructed diffraction gratings with which he determined the wave-lengths of the principal lines. Their actual physical significance, however, was unknown to him, and their tremendous importance was not realized till 1859, when Kirchhoff explained them and published the law which is known under his name.

A solid body raised to incandescent heat emits a perfectly continuous spectrum.

A gas raised to incandescence emits a discontinuous spectrum, or one composed of bright lines.

If a luminous gas is placed in front of a luminous solid the spectrum will be composed of the gaseous lines superposed on the continuous background.

Kirchhoff showed that a luminous gas had powers of absorption for rays of the same wave-length as it emitted, and that the relation between the powers of emission and the powers of absorption for rays of the same wave-length is constant for all bodies *at the same temperature*.

If the temperature of the gas be such that its emissive power is more intense than the emission absorbed, the effect will be brighter lines on a continuous bright spectrum. If, on the other hand, its own emission is less intense than the emission absorbed, the resulting spectrum will be a bright continuous spectrum crossed by dark lines—what is called an absorption spectrum.

The former effect occurs in certain stars, the latter in the case of the sun.

The dark lines in the spectrum of the sun can now be readily understood.

The interior body of the sun is intensely hot but at such a pressure

that, like a solid, it emits a continuous spectrum. It is surrounded by an atmosphere of cooler incandescent gases of many substances which act as filters, and absorb from the continuous spectrum those rays corresponding in wave-length to the rays which they themselves emit. This envelope is called the reversing layer, because the process of absorption causes dark lines in place of the bright lines obtained in the emission spectrum of a substance. The Fraunhofer lines thus furnish the key in the determination of the chemical composition of the sun, the existence of an element in the sun being proved by the coincidence of its characteristic lines with absorption lines in the solar spectrum.

Comparison of emission spectra with the solar spectrum may be made directly by bringing the two spectra side by side, when the coincidence of certain lines will be evident. This, however, is not always practicable, and it is therefore more usual to determine the absolute wave-lengths of the lines of an element and compare them with the absolute wave-lengths of the lines of the solar spectrum. For this purpose the map of the normal solar spectrum covering the visual region from A to H was published by Ångstrom in 1868. This is now superseded by Rowland's tables of the solar spectrum produced photographically, and extending to the limit imposed by atmospheric absorption.

The Spectroscope.—The undulatory theory supposes light to consist of transverse vibrations in an all-pervading medium called the ether. The vibrations or waves are similar to those produced on the calm surface of a pond when a stone is dropped into the water. They may be of any length, but all travel with the same velocity *in vacuo*. On entering a denser medium, however, their velocities are diminished, the shorter waves in greater proportion than the long waves. This causes the phenomena of refraction and dispersion.

Light emitted from a point at a given instant will leave at the same phase, and, travelling in all directions, will at any later instant, without interference, be in phase on the surface of a sphere. The surface at which all waves are intersected at the same phase is called the wave-front, and methods of physical optics show that the direction of propagation of light at each instant is at right angles to the wave-front.

The Action of a Prism.—A beam of light, which at a certain instant presents the front *ac*, begins to enter the denser medium of the prism at *c* (fig. 11).

In consequence of the less velocity in the denser medium the light from c moves only to c_1, whilst that from a moves to a_1, so that the lower portion of the light-front is thereby turned to b_1c_1. Successive portions of the light-front are shown at $a_1b_1c_1$, $a_2b_2c_2$, a_3c_3.

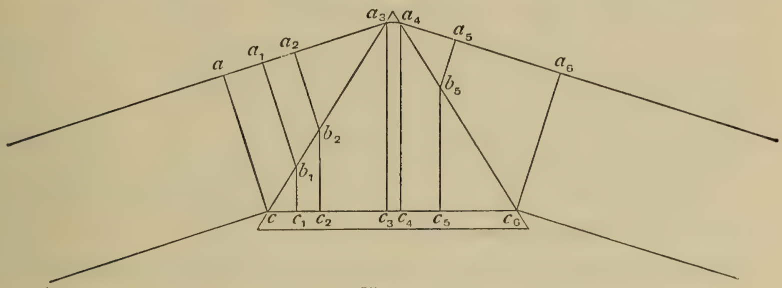


Fig. 11

When the light from a_4 emerges from the prism it begins to proceed more rapidly than that from c_4, which is still being retarded, and the wave-front finally emerges in the direction a_6c_6.

The difference of direction depends on the fractional difference of velocity of the ray in the two media and, since this is greater for the violet or the short waves which are retarded more than the red or long waves, it follows that a beam containing both will be split

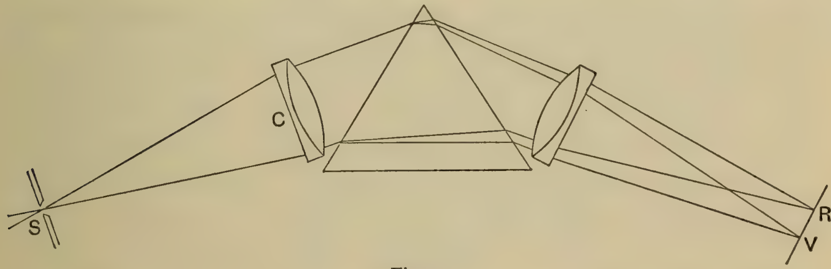


Fig. 12

up, the violet being more bent than the red. Such action of the prism is called *refraction*, the difference in direction of the entering and emerging rays is the *deviation*, and the difference of direction of the various colours is the *dispersion*.

Fraunhofer's spectroscope consisted of a slit, a projecting lens, a prism, and a viewing telescope. The prism spectroscope of to-day is not greatly different (fig. 12).

The spectrum is a series of images of the slit S, each in light of a different wave-length, consequently the purity of the spectrum

and the definition of the lines will depend on the width and shape of the slit. This is therefore made of metal; the jaws are finely ground to a chisel edge, and provision is made whereby the width may be varied at will.

It is desirable that the beam falling on the prism should be composed of parallel light, and this is effected by introducing the collimating lens C immediately before the prism, with the slit in its principal focus.

When the beam emerges from the prism, it is received by another lens which condenses the rays to a focus to be viewed by an eye-piece, or, as is usually the case, to be received on a photographic plate at RV, the red at R and the violet at V.

For the complete adjustment of a prism spectroscope it is necessary that the following conditions be satisfied.

1. That the collimating lens direct a beam of parallel light on the first prism face.

2. That the optical axes of the collimator and camera pass through the principal plane of the prism.

3. That the slit be parallel to the refracting edge of the prism

It can be shown that the angle of divergence of the emerging beam is at a minimum only when the angles of incidence and emergence are equal, and when the ray passes through a principal plane, i.e. a plane perpendicular to the refracting edge of the prism. It will follow that if the incident beam is very convergent or divergent, the resulting aberrations will militate against the best definition in the spectrum obtained. The focusing of the collimating lens so that it shall produce a parallel beam may be effected by utilizing the astigmatism which the prism introduces. If the slit is not in the focus of the collimator, then, when the slit is nearly closed, it will be found that the " dust " lines, running along the spectrum and caused by dust on the slit, will not focus simultaneously with the spectral lines, but will be a little inside or outside. By tentatively altering the focus of the collimator in or out, and refocusing the camera, these will presently be brought into focus together, and the first condition will be fulfilled.

When this is done it will be found that if the slit is of any considerable length, the lines will not be straight, but curved. This is due to the fact that only those rays which pass through a principal plane are at minimum deviation. Only those from the centre of the slit can pass through a principal plane. The lateral rays are

slightly inclined, and consequently suffer a greater amount of deviation, and the greater the distance the starting-point of the rays is from the centre of the slit, the greater will the deviation be. The lines are therefore concave towards the violet end of the spectrum. The second condition is fulfilled when the arc at its centre is normal to the direction of the spectrum.

If the slit is inclined to the refracting edge of the prism the spectral lines will be inclined to the spectrum. The slit must be adjusted until they are at right angles.

Although the physical conditions of the stars may be studied with advantage from spectrograms taken with the slit spectroscope, this form of spectroscope is perhaps of greatest use for determining stellar motions in the line of sight by means of the Doppler-Fizeau effect.

If a star is approaching the earth with a velocity v, the effect is to shorten each wave of light reaching the earth.

If c is the velocity of light,
λ the original wave-length,
λ_1 the apparent wave-length,

$$\text{then} \quad \lambda - \lambda_1 = \frac{v}{c}\lambda,$$

and the lines will be displaced in this proportion. If they are displaced toward the violet, approach is indicated, whilst if towards the red, recession.

The motion indicated by a displacement of any line of known wave-length is easily calculated.

The velocity of light c is 300,000 Km. per second.

The wave-length λ of the hydrogen line H_β is 4861 tenth metres.

If the wave-length is apparently 4860,

$$\text{then } v = c\frac{\lambda - \lambda_1}{\lambda}$$

$$= 300{,}000 \frac{1}{4861} = 62 \text{ Km. per second, approaching.}$$

To measure such small displacements the stellar spectrum must be compared with that from a terrestrial source. Iron or titanium vaporized in the electric arc or spark is generally employed because of the abundance and sharpness of lines suitable for measurement. The comparison spectra are printed on either side of the

stellar spectrum, and as near as possible without interfering, so as to reduce the correction for curvature of the lines to a minimum.

For this purpose the slit is provided with a shutter which can be manipulated so that through small apertures in it any portion of the slit may be exposed at will.

In taking the photograph the shutter is placed so that a short length at the middle of the slit is uncovered. The star is placed on the slit and caused to travel backwards and forwards, so that the resulting spectrum is broadened into a band of sufficient width to make the lines visible. A comparison spectrum is put on the photograph by covering the part of the slit through which the star was exposed, and uncovering a part at the side. The arc or spark is then projected on to this part of the slit by means of a condensing lens, and exposure for as long as is necessary is given. It is necessary to give at least two exposures on the comparison spectrum, one at the commencement and one at the end, and these would be on either side of the stellar spectrum. The two exposures provide a check on the constancy of the spectroscope, any change being shown as a displacement between the two comparison spectra.

Another method of throwing in the comparison spectrum, and probably a better one as it does not require dangerous handling of delicate mechanism in the vicinity of the slit, is the use of two minute total-reflecting prisms, whose edges define the length of the slit devoted to the star, placed immediately in front of the slit. The comparison spectrum may be thrown in from the side as often as desired without interrupting the exposure on the star spectrum.

Of the several methods devised for viewing the star on the slit, so that it may be kept there during a long exposure, the following is neat and effective.

The slit is made of speculum metal, its outer surface polished, and it is tilted at a small angle to the normal. The diameter of the stellar disc is greater than the width of the slit, and the light which does not pass into the spectroscope is reflected back at an angle to the incident beam. When intercepted by a reflecting prism and viewed with a small telescope, the star image is seen projected on the slit.

The photographs are measured in a micrometer, the position of the lines in the comparison spectrum being compared with the corresponding lines in the star spectrum, and the displacement of the star lines is interpreted as motion in the line of sight.

This work has been carried on very successfully at the great American observatories, and a wonderful degree of precision attained.

It has been pointed out that the motion of the sun in space towards right ascension 18 hr. and declination $+30°$ is deduced from the average trend of the proper motions of the stars. From the average trend of the spectroscopic line-of-sight velocities is determined not only the direction but the amount, and this Professor Campbell places at 20 Km. per second.

The Doppler-Fizeau principle has also been applied to the determination of the sun's period of rotation. From the observed period as determined from sun-spots it is known that the east point of the sun's equator is approaching the earth at approximately 2 Km. per second, whilst the west limb is receding at a similar rate, consequently the lines will be displaced towards the violet for the east and towards the red for the west. By arranging two total-reflecting prisms before the slit, the two spectra from opposite edges of the sun can be brought into contact and the displacement measured. This method is suitable for visual observation. For photographic observation the two opposite edges may be brought on to the slit successively, arranging by shutter that they do not interfere. The absorption lines introduced into the two spectra by the water vapour and oxygen in the earth's atmosphere are not displaced in the spectra, like those of solar origin, but appear as straight lines across both spectra. This provides an excellent check on all instrumental displacements.

Whilst the results by this method were in general agreement with the sun-spot period of rotation, Adams with powerful apparatus at Mount Wilson arrived at the surprising result that lines in a high level of the solar atmosphere gave a shorter period than those in a lower level.

The Objective Prism.—It is possible to study the physical condition of a star without the slit spectroscope. A star image is a point of light, and if the star light passes through a prism, and is then by means of a lens brought to a focus, it will be drawn out into a perfectly pure spectrum without the interposition of slit or collimator. It is, however, merely a line of light too narrow to permit of the spectral lines being visible, but, if widened by some device, becomes a well-defined band suitable for examination. In the slit spectroscope much of the light is lost on the slit and never reaches the photographic plate. With the objective prism the whole of the light (except that lost by absorption and reflection) falls on the plate, so that with comparatively small apparatus useful spectra of quite faint stars may be obtained. Further, with a lens covering a

large field it is possible to obtain good spectra of many stars with a single exposure.

With such apparatus the New Draper Catalogue of Spectra of a quarter of a million stars has been produced by Harvard College Observatory. The Bache telescope with which the work was commenced is a photographic doublet having an aperture of 8 in. and a focal length of 45 in. The field covered was about 10° in diameter.

Spectra were formed by placing over the objective of the telescope a square prism of dense flint glass 8 in. on a side, and having a refracting angle of about 13°. Another prism having a refracting angle of about 5° was also occasionally used.

The spectra so formed had a dispersion such that the intervals between the lines H_β (λ 4861) and H_ϵ (λ 3970) were 5·8 mm. and 2·2 mm. respectively. This telescope was used at Arequipa in Peru to photograph the southern stars, whilst a similar telescope was used at Cambridge, Mass., to photograph the northern stars.

With the larger dispersion satisfactory spectra were obtained of stars as faint as the 6th magnitude; with the smaller dispersion, still fainter stars.

A device was later employed by which the dispersion might be varied at will to suit the faintness of the stars it was desired to reach. Two prisms having nearly equal angles of 6° were mounted so that they could be rotated by any desired amount. When placed in opposite directions they nearly neutralized each other, whilst when turned in the same direction the dispersion was double that of one of the prisms.

The method of observing was simple. The prism was placed over the objective with its refracting edge parallel to the equator (the telescope of course was mounted equatorially), so that the spectrum was drawn out into a line running north and south. The line was broadened into a band by giving a rate to the driving clock slightly different to the correct sidereal rate.

The quality of the spectra so formed is inferior to those produced in a slit spectroscope, principally because the definition of the spectral lines is dependent on the quality and steadiness of the star images, which on a poor night may leave much to be desired. Apart from loss of light the slit spectroscope does not suffer from this cause. Also with the objective prism one has little or no control over changes of temperature and flexure.

The spectra are, however, perfectly good for examination of their main features.

The purpose of the work was the classification of the stars according to their physical condition.

The first systematic classification of stellar spectra was made by Secchi in 1867 as a sequence of four main types depending chiefly on the number and intensity of the lines, but the classification now generally adopted is that developed at Harvard from the detailed study of the spectra produced as described above.

The spectra were divided into groups, lettered alphabetically, and intended to follow the order of evolution. The original lettering has been retained, though in the light of later knowledge the order has been altered somewhat, and some groups, considered unnecessary, have been dropped. The most noteworthy facts which these studies have brought to light may be thus summarized. The spectra of the stars show few radical differences in type. More than 99 per cent of them fall into one or other of the six great groups which were recognized as of fundamental importance. These received the designations B, A, F, G, K, M.

Also they form a continuous series, so that intermediate types may be written as a decimal fraction; for example, B5A represents a type midway between B and A. Of the remainder almost all fall into four classes denoted by the letters P, O, R, and N, of which O undoubtedly precedes B, whilst R and N come probably at the other end of the series.

It would appear that in general the composition of all stars is identical, the principal differences in the spectra arising in the main from variations in a single physical variable in the stellar atmosphere—the temperature.

The criterion adopted for stellar classification is the varying intensity of particular groups of absorption lines in the stellar spectrum.

Thus helium absorption lines first appear at Oe (in preceding classes they are bright), gradually growing stronger, reaching a maximum intensity at B2, and then weakening till at B9 they disappear.

The hydrogen lines, bright in P, Oa, Ob, and Oc, appear as absorption lines in Od, which reach a maximum at Ao, and then weaken until they disappear at Mb.

Calcium, as represented by the high temperature or ionized lines at H and K, makes its appearance at Od, reaches its maximum intensity at Ko, and goes out at Md.

Calcium, as represented by the low temperature line 4227, first appears at B8, growing stronger to the end of M.

Saha [1] shows that this behaviour of the lines in the spectra may be explained on the theory of the ionization of the atoms due to increasing temperature as one proceeds from the Md type with a temperature of 4000° C., through G with a temperature of 7000° C. (the sun is a dwarf star of this class), to O with a temperature of 22,000° C.

At the head of the list, class P comprises the gaseous nebulæ distinguished by the bright nebular lines 4959 and 5007, whilst at the other end the M classes are distinguished by banded spectra, titanium oxide flutings becoming prominent.

In addition to these special features it is notable that in the progress from B to M the intensity of the blue end weakens relatively to the red end. Use has been made of this fact to determine the colours of stars as defined by the wave-length of maximum photographic radiation.

Effective Wave-length.—When a coarse grating is placed before an objective, short diffraction spectra are produced in the focus on either side of the central image, the distance between the central and diffracted images being a function of the grating interval, the focal length of the objective, and the wave-length of the light of the star.[2]

If a is the clear space between the bars,
d the width of the bar,
f the focal length of the objective,
D the measured distance between the two first order spectra,

$$\text{then } \lambda_{\text{eff.}} = \mathrm{D}\frac{a + d}{2f}.$$

If B is the brightness of the image without the grating, B_m that of the mth lateral image:

$$\mathrm{B}_o = \mathrm{B}\frac{a^2}{(a + d)^2}.$$

$$\mathrm{B}_m = \mathrm{B}\frac{1}{m^2\pi^2}\sin^2\frac{am\pi}{a + d}.$$

When bar and space are equal these become

$$\mathrm{B}_o = \tfrac{1}{4}\mathrm{B}.$$

$$\mathrm{B}_m = \mathrm{B}\frac{1}{m^2\pi^2}\sin^2\tfrac{1}{2}m\pi.$$

In this case the first order spectrum contains the utmost amount of light obtainable in any spectrum, and

[1] *Proc. Roy. Soc.*, Vol. A99, No. 697.
[2] Article on "Diffraction" by Rayleigh, *Encyclopædia Britannica.*

$$B_1 = \tfrac{1}{10}B,$$
$$B_2 \text{ disappears},$$
$$B_3 = \tfrac{1}{9}B_1.$$

Some work on these lines was commenced at Greenwich Observatory[1] with the object of supplying an indication of spectral type of stars fainter than those included in the Draper catalogue. Employing a 30-in. reflector and a grating made of wire approximately 1·5 mm. in diameter, and spaced at 3 mm. (i.e. bar and clear space equal), the distance between the first order spectra on the photograph is about 1 mm. With a 10 minutes exposure it was possible to obtain measurable images of stars of the 11th magnitude.

When comparison was made of measured wave-length and spectral type as given in the Draper catalogue the following result was obtained.

Spectral Type.	Eff. Wave-length.	Spectral Type.	Eff. Wave-length.
Oe5	4074	F2	4269
B2	4148	F5	4285
B3	4150	F8	4296
B5	4174	Go	4306
B8	4242	G5	4394
B9	4230	Ko	4468
Ao	4261	K2	4496
A2	4271	K5	4538
A3	4273	Ma	4538
A5	4271	Mb	4491
Fo	4275	N	4572

It will be observed that the progression of wave-length against spectral type is not linear. Whilst there is a very definite gradient from B to A and from G to K5, there is a distinct pause from A to G. This is unfortunate, as it prevents the use of effective wave-lengths as an accurate means of spectral classification on the Harvard system. The method does, however, provide a means of classifying colours of stars to a low magnitude.

An excellent method of determining the relative colours of stars is that invented by Professor Seares of Yerkes Observatory, and described as the method of exposure ratios.

Using a reflecting telescope because of its perfect achromatism

[1] See also Hertzsprung, *Astrophys. Journal,* Vol. XLII., 1; Lindblad, *Arkiv. för Mathematik,* &c., Stockholm, Bend 13.

and an isochromatic plate, exposure is made on a field of stars first through a blue filter, and secondly through a yellow filter. The yellow filter being very absorptive, an increase of exposure of about 8 to 10 times is necessary in order to obtain images comparable in density to those taken through the blue filter.

For example, with the blue filter exposures of 20 sec., 1 min., and 3 min., and with the yellow filter 160 sec., 8 min., and 24 min. are given, on one plate, displacement being made after each exposure. The images might be conveniently arranged in two columns, the blue images in one column and the yellow in a second column beside them.

If the star is strong in blue light the blue images will appear the darker, whilst if red predominates then the yellow images will be stronger. The ratio must be determined from standard stars.

Absolute Luminosity.—We have hitherto spoken of the spectra of stars as forming a continuous series with one variable—the temperature of the star. We now know this is not quite correct. It was first suggested by Lockyer and later proved by Russell that in the spectra we have the life-history of a star. At its birth it is of enormous size, little density, low temperature, and red in colour. By the attractive force of gravitation the star gradually condenses, and of necessity grows hotter and whiter until it reaches that stage when the heat radiated balances the heat produced by contraction. It is now at its hottest, and from this point onwards gradually cools, going backward through the same colour stages through which it passed to its maximum. At its birth it is an M type star. As it condenses it passes through the types K, G, A, to B, the hottest and whitest stage it can reach, then continuing cools through A, G, K, to M. On the ascending grade it is termed a giant, on the descending grade it is called a dwarf. The sun is a dwarf of the G class.

Till recently no difference was recognized between spectra of giants and dwarfs of the same type. From a close study of the spectra of known giants and dwarfs, Adams and Kohlschutter of Mount Wilson Observatory discovered certain small differences.

1. The continuous spectrum of the giant or high-luminosity stars is relatively fainter in the violet as compared with the red than is the spectrum of the dwarf or low luminosity stars.

2. In certain types the hydrogen lines are stronger in the giants than in the dwarfs.

3. Certain other lines are weak in the dwarfs and strong in the giants and conversely.

This suggested the possibility of inferring the absolute magnitude of a star from a study of its spectrum.

After careful consideration No. 3 was chosen as affording the most satisfactory criterion as to absolute luminosity, and the following four lines were selected for the purpose.

Line.	Element.	Stars.		Spark.	Arc.
		High Luminosity.	Low Luminosity.		
4077	Sr	Strong	Weak	Strong	Weak
4215	Sr	,,	,,	,,	,,
4290	Ti	,,	,,	,,	,,
4455	Ca	Weak	Strong	Weak	Strong

The conclusion is obvious that the enhanced or high temperature lines 4077, 4215, 4290 are strong in high-luminosity stars, whilst the low temperature line 4455 is weak in the high-luminosity stars. This does not necessarily imply a higher temperature in the high-luminosity stars, as vapour density has an important effect on line intensity.

Absolute luminosity was inferred by comparing these sensitive lines with others near and similar in intensity, but which were not affected by the stars' luminosity. These comparison lines were the iron lines 4072, 4250, 4271, 4462, and 4495.

All these lines were not equally suitable for all types.

For stars of type A to F7:

4077 Sr was compared with 4072 Fe.
4290 Ti ,, ,, 4271 Fe.

For types F8 to G:

4077 Sr was compared with 4072
4215 Sr ,, ,, 4250
4290 Ti ,, ,, 4271
4455 Ca ,, ,, 4462
4455 Ca ,, ,, 4495

For types G to M:

4215 Sr was compared with 4250
4455 Ca ,, ,, 4462
4455 Ca ,, ,, 4495[1]

[1] *Astrophys. Journal*, Vol. LIII, p. 13.

The spectra on which the Mount Wilson work was done were taken with a slit spectroscope. It has since been found that good objective prism spectra are quite suitable for the purpose, and Harvard are already examining their spectra to this end. Dr. Lockyer at the Norman Lockyer Observatory at Sidmouth is also employing an objective prism in the work.

The Spectroheliograph.—The spectroheliograph, invented independently by Hale and Deslandres about the year 1890, is an instrument designed to photograph the solar disc by means of monochromatic light of any desired wave-length.

The general disc of the sun gives a dark-line absorption spectrum;

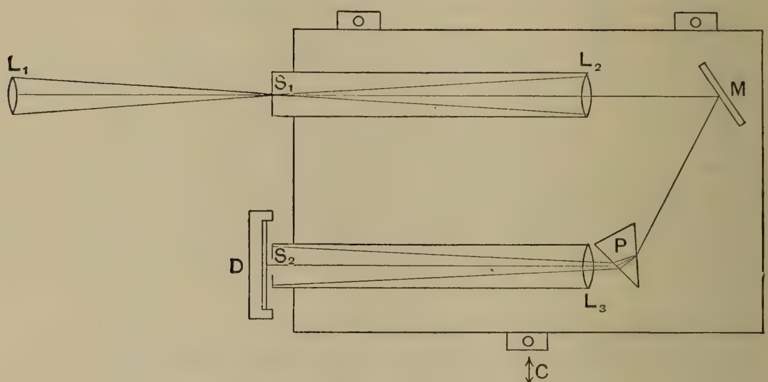


Fig. 13.—Diagrammatic Arrangement of Spectroheliograph

but we have seen that these lines are dark only relatively to the bright continuous spectrum of the hotter background. When isolated from the continuous spectrum the line will be a bright line emanating the radiation due to the incandescent gas of which it is characteristic. It is also a picture in light of that particular wave-length of the distribution of the gas over the area covered by the slit. If the slit is caused to traverse the solar disc, successive pictures will be formed which, when joined up, will give a complete picture of the sun in light of that wave-length, showing the distribution of that gas and no other.

This is the principle employed in the spectroheliograph, and its general arrangement is shown in the accompanying diagram (fig. 13).

L_1 is a telescopic objective, generally of long focal length to give as large a primary solar image as possible on the first slit S_1 of the spectroheliograph.

Light passing through this slit is parallelized by the collimating lens L_2, and is then directed by a plane mirror M on to the prism or grating P. Here it is split up into a spectrum band which is focused by the camera lens L_3 on the secondary slit plate S_2.

Means is provided for delicate adjustment of S_2 along the spectrum, so that a line of any desired wave-length may be allowed to pass through S_2. All the rest of the spectrum will be stopped by the slit plate.

A photographic dark slide D is arranged in an independent support so as to bring the sensitive surface as near as possible to the plane of the slit S_2.

Thus far we have a means of isolating any desired wave-length of the spectrum of whatever source of light falls on the first slit S_1.

In order to photograph the details of any area, therefore, it is only further necessary to provide for the whole of the spectrograph, including collimator, mirror, prism, and camera, to be moved uniformly across the area to be examined in a direction perpendicular to the length of the slits S_1, S_2.

To do this the instrument is mounted on a rigid platform, which is in turn supported on three hard steel balls, with provision for rectilinear motion, and a regulator C to ensure that the transverse motion is uniform.

The light usually employed is that of hydrogen, using the bright line H_α, or that of calcium, which is prominent in faculæ, and is characterized by two very strong lines in the ultra-violet at wave-lengths 3968 and 3933, usually designated H and K respectively. That at 3968 is generally associated with a neighbouring line of hydrogen 3970, so for greater certainty the K line is chosen for isolation. By means of the adjustments of the secondary slit S_2 its position is found when this line is exactly centrally transmitted. Then the solar image is adjusted centrally on the primary slit plate S_1. The photographic plate is inserted in the dark slide D, and the shutter withdrawn. Now the whole instrument is displaced until the primary slit is beyond the solar disc, and then released, so that a focal plane exposure is made by the primary slit gradually passing from one edge of the sun to the other.

During this time the secondary slit will have been passing radiation of calcium light to the plate from all portions of the sun where this happens to be showing bright. By prolonging the exposure the whole of the sun's calcium atmosphere with the prominences may be photographed. Also by using monochromatic

radiation of hydrogen, iron, &c., it is possible to determine the distribution of these elements over the solar surface.

Various modifications of the instrument are in use in many different parts of the world, and the results obtained from this method of investigation have provided important additional information concerning the constitution of the solar atmosphere.

Hale in 1908 observed that photographs of the hydrogen flocculi showed marked vortical structure in regions centring in sunspots. These photographs suggested the hypothesis that a sunspot is a vortex in which electrified particles, produced by ionization of the solar atmosphere, are whirled at high velocity, giving rise to magnetic fields in sunspots. A search for the Zeeman effect led to its immediate detection and the consequent proof of a magnetic field in every sunspot observed.

Zeeman discovered that if light is passed through a strong magnetic field certain single lines in its spectrum are turned into doublets or triplets.

When the light is viewed *across* the lines of force, the spectrum line is seen to be split symmetrically into three lines, and each line is plane polarized, the two side (*n*) components having their planes of polarization parallel to the lines of force, and the middle component (*p*) with its plane of polarization perpendicular to the lines of force.

When the light is viewed *along* the lines of force the central (*p*) component is absent, and the two side (*n*) components are circularly polarized in opposite directions. If a quarter wave plate and a Nicol prism are mounted over the slit of the spectroscope, then the circularly polarized light is converted into plane polarized light, and by rotating the Nicol either *n*-components can be cut off at will. Further, if the polarizing apparatus be adjusted so as to extinguish one component, reversal of the current through the coils of the magnet (or change of polarity) will cause this component to reappear while the other will be extinguished. Also, the amount of the separation of the components depends on the strength of the magnetic field.

When a sunspot is placed on the slit of the spectrograph, some of the spectral lines are found to be strengthened and others weakened. Part of the change is attributable to the difference of ionization of the elements in the relatively cooler spot and the surrounding region. More is, however, due to the Zeeman effect, and by means of the polarizing apparatus the affected lines may be

analysed, and the direction of polarity and strength of field deduced.

This method is employed daily for the study of the magnetic polarity of sunspots with the 75-ft spectrograph of the 150-ft. tower telescope at Mount Wilson.[1]

By an extension of this principle the elements of the sun's magnetic field as a whole have been recently determined from a discussion of a large number of photographs.

Solar Eclipses.—Very little could be accomplished without photography in delineating the solar corona during the fleeting moments of the total phase of an eclipse of the sun, but with its aid this presents little difficulty. As total eclipses usually occur in places not easily accessible, the difficulty is usually one of transport of the necessary apparatus; consequently, when it is desired to take large-scale photographs with lenses of great focal length it is usual to employ the cœlostat to reflect the beam into the telescope, which may be placed horizontally in a convenient position. The only moving part is the mirror of the cœlostat, which is driven by clockwork at the rate necessary to keep the sun's image stationary on the photographic plate.

In the observation of the Einstein gravitational displacement, special precautions must be taken.[2]

The Einstein theory of gravitation requires that a ray of light passing near the sun shall be bent in towards the sun just as if light had mass, but the deflection would be twice as great as that required by the Newtonian law.

If a star could be observed when in such a position that its light grazed the edge of the sun it would appear to be displaced *outwards* from the sun by 1·″75. At 2 radii from the sun's centre the displacement would be 0·″88 at 3 radii 0·″58 and so on in inverse proportion to the distance from the sun's centre. Such an observation can only be made during a total eclipse.

If a photograph of the stars near the sun is taken during the eclipse and compared with another photograph of the same region when the sun was not in the vicinity it should be found that on the eclipse photograph the stars very near the sun are displaced more than those more distant. This method was employed at the eclipse of May, 1919, and the result supported the Einstein theory. The

[1] Hale, &c., *Astrophys. Jour.*, Vol. XLIX.

[2] For a discussion of the legitimacy of small measurements on photographic plates, from the point of view of the physical chemistry of the film itself, see p. 200, *et seq.*

disadvantage of this method is that one cannot use the total Einstein distortion, but only the difference between that of the near and the more distant stars; consequently if there are no bright stars near the sun the difference of displacement of the outer stars is small. At future eclipses it will be desirable to employ another method. A field of stars conveniently placed, but not near enough to be gravitationally affected, will be photographed on the same plate with the affected field *during* the eclipse. Later, when the sun has moved away, the two fields will be again photographed together on another plate. A very complete check on the scale of the photographs is thus provided and admits of the determination of the total Einstein displacement.

The spectrum of the chromosphere used to be a feature of great interest at eclipses, but this can now be observed at least as well with the large apparatus at Mount Wilson without an eclipse.

There are few branches of astronomy which do not benefit from the application of photography. It is true that in the observation of double stars, photography cannot compete with the visual observer when dealing with very close difficult pairs, but with the wider pairs its assistance is of great value.[1] Hertzsprung at Potsdam has done some very fine work in the photography of double stars, taking special precautions to avoid the errors caused by atmospheric dispersion on differently coloured stars. This he did by photographing with only a narrow band of spectrum in the yellow, thus reducing both stars to the same colour.

In the drawing of planetary detail the skilled observer has the advantage over the photograph, as he is able to make use of the momentary periods of fine definition, but even here the photograph has proved a valuable corroborative witness.

[1] See p. 200.

CHAPTER VI

Application of Photography in Physics

In all branches of physics there are many problems in the solution of which the aid of photography has been successfully invoked. Many of these would yet remain unsolved but for that aid, while the solution of others would have been much more tedious and less accurate. Among the former may be mentioned the interesting work of Professor Boys on the flight of bullets, while the more recent work on positive rays, throwing so important a light on the constitution of atoms and molecules, may be classed with the latter type of problem. In certain cases, such as in X-ray photography, special photographic plates are used, but in the great majority of cases in which photography is applied to physical investigations, ordinary commercial photographic plates and apparatus only are required, and it is in the arrangements of the physical experiment necessary in order to produce the required " picture " that the chief care is required. An appreciation of the difficulties involved in various types of experiment and of the way in which these difficulties have been overcome, may best be obtained by a description of selected investigations in the various branches of physics, and these examples will serve to indicate how similar investigations may be successfully accomplished. A description of the special plates, plate carriers, and cameras, where such are required, is included in the description of the appropriate experiment.

Mechanics: Instantaneous Photography.—There is a large group of problems in mechanics in which it has been required to obtain an instantaneous photograph of an object moving at such a speed that any mechanical shutter is far too slow. In some cases the actual speed of the object is very high, while in others the object is small and has to be placed near the camera, so that the angular movement is large. In either case, resort is had to a camera with uncovered lens directed to the object, on which a brilliant light plays for a very short period of time. The experiment must, of

course, take place in a darkened room or in an enclosed darkened box. The light is produced by the spark discharge of an electrical condenser, and the period during which the light is maintained may be reduced to considerably less than one-millionth of a second. As an example of such a problem, in which, however, the time of illumination need not be so very short, the photography of ripples on the surface of a liquid may be described. From a knowledge of the wave-length and frequency of such ripples, the value of the surface tension may be deduced, and the phenomena of reflection and interference of waves may be studied. Fig. 1 (see plate) is a copy of one of many photographs of the ripples on the surface of a shallow layer of mercury, taken by Dr. J. H. Vincent.[1] The apparatus is shown diagrammatically in fig. 2. The spark is produced at the point S, which is placed at the focus of the lens L_1, and parallel light is thus cast upon the surface of the mercury in the shallow dish D. The reflected light is focused by a similar lens L_2 on to the object lens of the camera C, thus ensuring the maximum amount of light being received by the camera lens. The ripples are produced by the tuning-fork F, from the end of which projects one or more small stiles dipping into the mercury. Any make of rapid photographic plate may be used, and it is better to use a small stop and intensify the plate rather than use a larger stop. The camera may be focused by placing a fine thread on the surface of the mercury. A spark of great brilliancy and small length is required. Now if the two plates of an electrical condenser are connected to the two sides of a small spark gap, discharge would take place normally at a low potential difference with a small charge on the condenser plates, and a weak spark only would be obtained. This is remedied by the placing of a second and wider spark gap in the circuit, the potential of discharge being determined by the

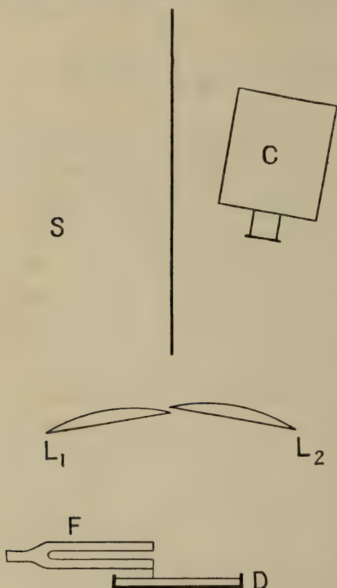


Fig. 2.—The Photography of Ripples—The Apparatus

[1] *Proc. Phys. Soc.*, Vol. XV.

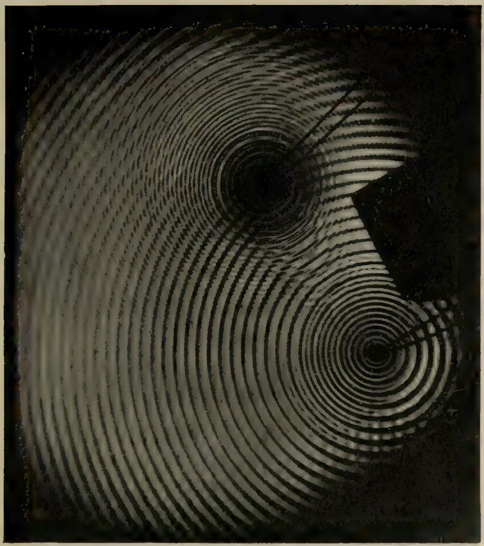


Fig. 1.—Mercury Ripples, by Dr. J. H. Vincent

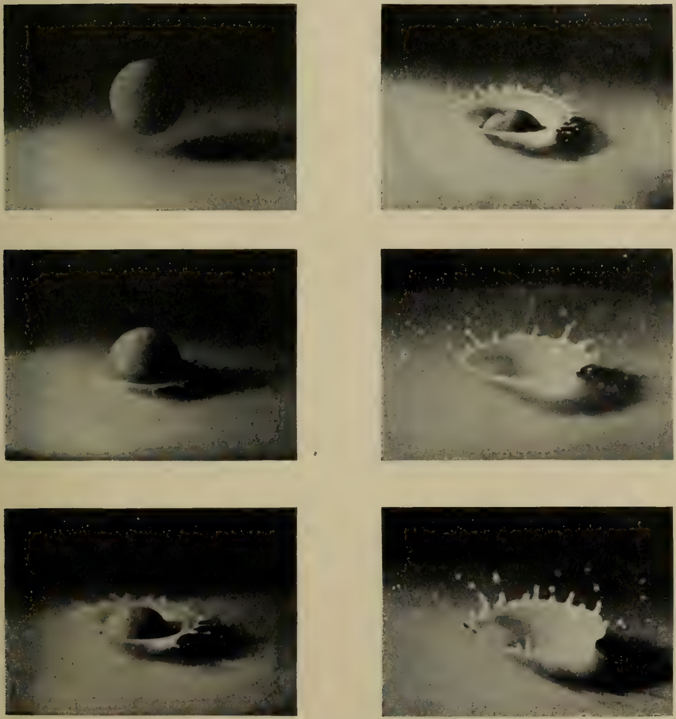


Fig. 7.—Initial Stages of a Splash
(From *A Study of Splashes*, by Prof. Worthington:
Longmans, Green, & Co., Ltd.)

Facing p. 262

width of the second gap. The arrangement is shown in fig. 3. A and B represent the terminals of a Wimshurst machine, which charges up the condenser R, consisting of four large Leyden jars in parallel. The spark gap used for the illumination of the mercury is shown at S and is about 0·5 cm. wide, while T is the larger spark gap about 1·5 cm. wide. The condenser is charged by the rotation of the machine until the potential of A is raised to the sparking potential of the gap T, and discharge takes place through both T and S. To prevent the formation of small sparks due to induction, the gap S is shunted by a piece of stout thread soaked in calcium chloride

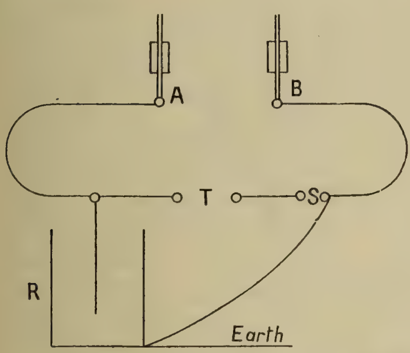


Fig. 3.—The Photography of Ripples—Means of getting Electric Spark

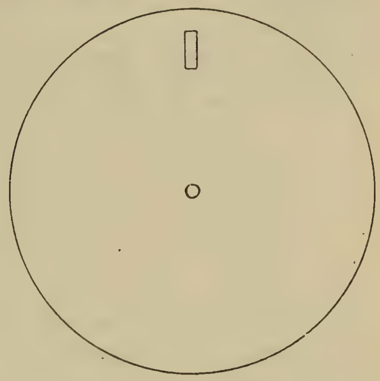


Fig. 4.—Periodic Motion and Ordinary Illumination—Exposure Disc

solution. The example shown in fig. 1 is a photograph of the ripples produced by stiles projecting from two forks, one of frequency 128 and the other of frequency 512 vibrations per second.

Now these ripples are moving outward from their centres, and, taking the case of those of lower frequency, after every $\frac{1}{128}$ part of a second, a ripple has moved out into the position previously occupied by the next. Hence if we have a shutter which will open for an extremely brief period of time at intervals of $\frac{1}{128}$ of a second, the same "picture" will apparently be presented although all the ripples have moved to the next position between successive openings. Using ordinary illumination instead of the electric discharge, a single opening of the shutter would be too small to make any impression on the photographic plate, but the cumulative effect of a large number of openings, all revealing the same picture, will be sufficient to do so. A shutter which will do the work required may be formed of a disc (fig. 4) having a

narrow radial slit, and rotated at a high speed, which is adjusted until the view of the ripples as seen through the slit reveals an apparently stationary image. A frequency equal to that of the ripples, or any submultiple of that frequency, will give the same effect, and it must remain perfectly constant during the exposure of the photographic plate. If the speed is too slow, the ripples will apparently move slowly outward, and if too high will move slowly inwards. A method which obviates the necessity of this troublesome adjustment of speed, is to use a shutter either in front of the camera or in front of the light, which is operated by the tuning-fork itself or by another of the same frequency. If two small pieces of light metal sheet are fixed to the prongs of a fork (fig. 5) so that their edges very slightly overlap when the fork is at rest, a space will be revealed between them when the prongs are apart during vibration. A light behind will shine through during this portion of the vibration but will be cut off during the remaining portion. In this way an intermittent illumination of the same frequency as the fork may be obtained. Whatever the picture to be photographed, a form of this method can be used where the machinery producing it with regular frequency is also available to work a shutter. The revolving disc method must be used if the machinery producing the picture is not available to work the shutter. Furthermore, for either method, exact repetition of the picture must occur. In fig. 1 each ripple in one set of ripples moves into the position of the next in $\frac{1}{128}$ of a second, and each ripple in the other set moves into the adjacent position in $\frac{1}{512}$ of a second. Exact repetition takes place every $\frac{1}{128}$ of a second, but if the frequencies were 127 and 512, exact repetition would only take place every second, in which period external causes would probably have disturbed the experiment or the vibrations would have died down. It is therefore only in rare cases that these methods can be used, whereas the spark method is of universal application.

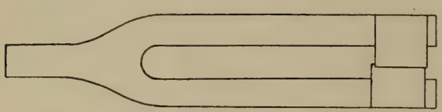


Fig. 5.—Periodic Motion—Tuning-fork Shutter

The motion of the ripples whose photography is described in the preceding paragraphs is comparatively slow, and it is not necessary to take special precautions to obtain a spark of very short duration. Furthermore, the photograph of the ripples was not required at any particular period of their motion. In cases of quicker motion,

and in cases where the spark is required to occur when the object is in a particular position, more complicated arrangements are necessary. A most instructive and interesting series of pictures of splashes, produced by drops and by balls falling into liquids, has been produced by Professor Worthington, whose method is illustrated in fig. 6. The ball or drop is first placed in the shallow dish D, at the end of a lever kept horizontal by the electromagnet M_1. If the current through M_1 is broken, the spring P causes that end of the lever to spring upwards and tips out the ball, which falls

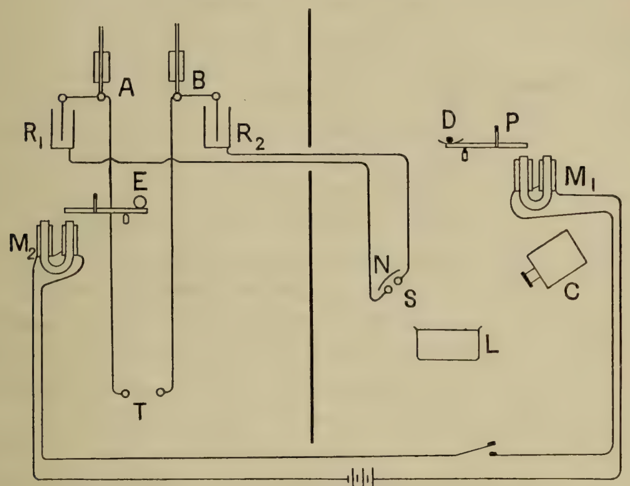


Fig. 6.—Professor Worthington's Method of photographing Splashes

into the liquid in the bowl L. This operation can be repeated with great exactitude, and pictures taken at different periods of the splash during a repetition of the process form a series representing any one of the splashes. The splash is illuminated by the spark at the gap S produced by the discharge of the outer plates of two large Leyden jars R_1 and R_2, and is photographed by the camera C. The terminals of S are made of magnesium, which produces a more brilliant light than other metals. A concave mirror N concentrates the light on the splash. The condensers are charged by a Wimshurst machine represented by its knobs A and B, which are connected to the inner plates of the condensers. The inner plates are also connected to the sides of a second spark gap T. The electric current which magnetizes M_1 also magnetizes a second electromagnet M_2, which operates a lever carrying a metal sphere E.

When the current is broken, the lever carrying E tilts simultaneously with the lever carrying D. The drop or ball from D falls into the liquid of the bowl L, while the sphere falls through and short-circuits the gap T. The condensers having been previously fully charged, the short-circuiting of T discharges the inner plates, followed by the discharge of the outer plates through S. The time at which discharge takes place can be varied at will by altering the distance through which the sphere has to fall before reaching T. Hence the photograph can be obtained at any period of the splash. By a series of tests on drops falling in front of a scale, it was found that the time at which discharge took place could be adjusted to $\frac{1}{500}$ of a second, while by photographing marks on the edge of a disc in rapid motion it was estimated that the duration of the spark was less than three-millionths of a second. The first six photographs of a series representing stages in the fall of a rough sphere into water, at intervals apart of 0·003 second, are shown in fig. 7 (see plate facing p. 262), reproduced from *A Study of Splashes*, by Professor Worthington. "Ordinary" photographic plates were used and afterwards intensified.

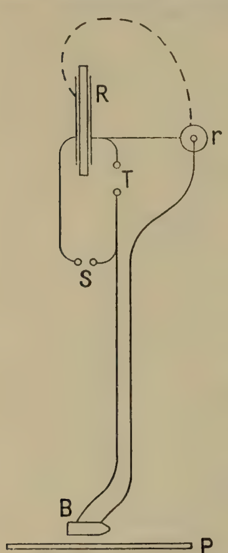


Fig. 8.—Professor C. V. Boys' arrangement for the photography of bullets moving at a speed of 1000 miles per hour.

As a final example of instantaneous spark photography, the experiments of Professor C. V. Boys on the photography of a bullet just discharged from a rifle and moving at 1000 miles an hour may be referred to. For this purpose a duration of spark of three-millionths of a second is considerably too great, and it was found possible to reduce it, or at least that portion of it which carried nearly the whole of the light, to about one ten-millionth of a second. The terminals of the spark gap were made of copper or platinum. Terminals of magnesium, although they greatly increase the brilliancy of the spark, prolong its duration, and were therefore replaced by those of less volatile metals. A parallel-plate condenser of 1 sq. ft. area with dielectric of window-glass was used, and the connecting wires were formed of very short thick bands of copper. The condenser was discharged by the bullet itself, the necessary arrangement of the circuit being shown in fig. 8. The spark gap by which the

photograph was taken is represented by S, the second gap by T, and the condenser by R. An additional small condenser *r* is in parallel with the larger one, being connected to one plate by a strip of copper and to the other by a string soaked in calcium chloride solution. Two wires from *r* and S form a third gap at B, which is closed by the passage of the bullet. The condensers are charged to a potential which is insufficient to produce a spark at S or T, but would do so at either if the other was made conducting. Similarly, if either B or T was closed, sparking would occur at the other. As the bullet passes and closes B, *r* is discharged through B and T. This spark is very feeble, the effect at B not appreciably affecting the photographic plate P which is quite near. The gap T, however, being thus rendered conducting, the large condenser R is discharged through S and T, the spark at S casting a sharp shadow of the bullet on the plate, and a silhouette photograph is obtained. If a single circuit only had been employed, the gap B taking the place of T, the sparking that would have occurred at B by the passage of the whole of the charge of R through S and B would have fogged the plate. A simple shadow photograph was obtained in preference to an image produced by a lens, in order to take full advantage of all the actinic rays which are produced by the electric spark and to avoid the absorption of them by the glass of the lens. An example of one of the photographs obtained is shown in fig. 9 (see plate), which is reproduced from *Nature*, Vol. XCVII. It will be seen that the image produced is perfectly clear and sharp. The inclined lines proceeding from the bow and stern are waves of compressed air, set up in similar manner to the waves of a boat moving quickly through water. The reflection of these waves when they strike a surface is also shown. Professor Boys has taken photographs of bullets at various stages of their flight when piercing a sheet of glass, and has indicated how many problems on the flight of bullets may be solved by this method. The apparatus has been reproduced and is now in use for this purpose.

Records of Oscillatory Motion in Mechanics, Sound, and Electricity.—In all branches of physics, and particularly in electricity, it is often necessary to obtain a continuous record of the oscillatory motion of a body about some mean position. The motion may or may not be regular and it may or may not repeat itself periodically. We will first consider a method available in all cases, and as the simplest example we will take the case of the vibrations of the prong of a tuning-fork. If a ray of light AB is incident

on a mirror B fixed on the side (not visible in the diagram) of the prong of a fork as shown in fig. 10, it will be reflected along BC, and as the fork vibrates the reflected ray will also vibrate through

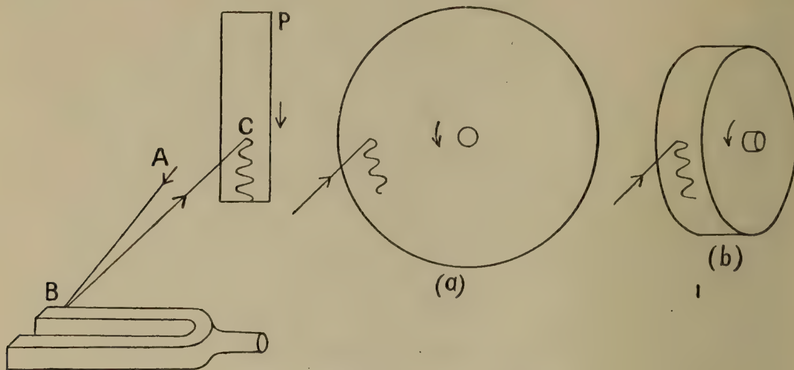


Fig. 10.—Records of Oscillatory Motion

an angle twice that described by the mirror. If the reflected ray is received on a photographic plate P, a horizontal straight line of short length would be described, but if P is allowed to fall vertically during the process, a curve is traced out showing the character of the vibratory motion of the prong. The time axis of the curve will be vertical, and its scale can be increased or diminished by adjusting the distance through which the plate falls before reaching the reflected beam. If falling freely under gravity, the increase in speed will also be shown by the lengthening of the scale towards the top of the plate. An arrangement for giving a uniform speed is described later. Instead of using a falling plate, the light may be received on a disc of sensitized paper, fig. 10, *a*, or on a cinematograph film or strip of sensitized paper wrapped round a drum, fig. 10, *b*; the disc or drum, as the case may be, rotating at uniform speed.

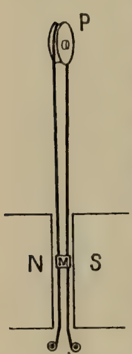


Fig. 11.—Duddell Oscillograph.

In the study of varying electric currents such as those in dynamos, motors, induction coils, and telephones, the current or a portion of it is passed through a galvanometer, known as an oscillograph, in which a deflection of a beam of light is obtained which is proportional to the varying current. One form of oscillograph is shown diagrammatically in fig. 11. In the narrow gap between the poles N and S of a powerful

magnet, are stretched two parallel conductors formed by bending a thin strip of phosphor bronze back on itself over an ivory pulley P. A spiral spring attached to the axis of this pulley serves to keep a uniform tension on the strip. A small mirror M bridges the gap between the two portions of the strip. The effect of passing an electric current is to cause one of the strips to advance and the other to recede, and the mirror thus turns about a vertical axis. With an alternating current, the mirror vibrates as in the case of that attached to the tuning-fork in fig. 10. In order to record accurately the variation of a high-frequency current, it is necessary that the natural period of the vibrator shall be very small, this being ensured by the tension and the very small moment of inertia. Two or more vibrators may be placed between the poles of the magnet in order to record simultaneously the same number of currents. If a vibrating tuning-fork of known frequency with mirror attached is also placed alongside, a tracing of its vibrations furnishes a means of obtaining a time-scale for the current oscillations. A fixed mirror gives a line parallel to zero current.

The optical system necessary to produce a sharply defined curve is as follows. The source of light is an arc lamp, the light from which passes first through a condensing lens and then through a vertical rectangular slit 10 mm. long and 1 mm. wide. The position of the lamp from the lens is adjusted till an image of the arc is obtained covering the mirrors. The light is reflected back from these mirrors, and, being condensed by a lens immediately in front of them, it converges till an image of the slit is formed on the surface where the record is desired. In order to convert this image into a bright spot, a horizontal cylindrical lens of short focal length is introduced. A reproduction of the curves obtained for the currents in the primary and secondary circuits of an ignition coil used in a motor-car engine is shown in fig. 12 (see plate facing p. 266) at A and B. The line C gives the direction of the zero line, and D reproduces the vibrations of a standard fork, whose frequency was about two and a half times that of the currents. This diagram was obtained by a plate falling freely under gravity, but the distance through which it had fallen was sufficient to give it a comparatively high velocity, and the time-scale is nearly uniform over the length of the plate. Any make of rapid plates can be used. The kind of arrangement for holding the plate is shown in fig. 13. The plate is contained in and falls freely down a long narrow box, a red cloth bag at the top serving to introduce the plate and another

at the bottom receiving it after its fall. A catch near the top holds the plate until it is desired to release it. Near the bottom of the box is a horizontal aperture through which the light is received on the plate as it passes. A simple arrangement of this character is not suitable where a slow-moving plate is required, as a small fall would give a considerable change of the time-scale along the length of the plate. A camera in which the velocity can be adjusted over a considerable range, but in which the velocity remains constant during the fall whether quick or slow, has been designed by the Cambridge Scientific Instrument Company, and is shown in fig. 14 (see plate). The diagram shows the back of the camera removed in order that the plate-carrier shall be visible. The slit through which the light passes is in the side not visible in the diagram. The plate is carried in a dark slide H which is inserted in the carrier G, fixed to cords C. These cords pass under the pulleys D and over a corresponding pair (not visible) in the top of the camera, and as the plate and carrier fall, the cords turn the upper pulleys and the shaft to which the outside pulley W is fixed. A cord fixed to W, operating through the arm P and the rod O, tends to force down the piston B which fits accurately into the cylinder of oil A. The piston B contains a valve through which the oil must pass from below to above the piston, and the rate at which B can fall is regulated by the rate at which the oil can flow through the valve, and becomes quite constant after a fall of a very short distance. The speed can be adjusted by changing the valve opening by means of the graduated wheel X. In order that the piston can be lifted quickly, it is fitted with a second non-return valve through which the oil can flow freely back into the lower part of the cylinder.

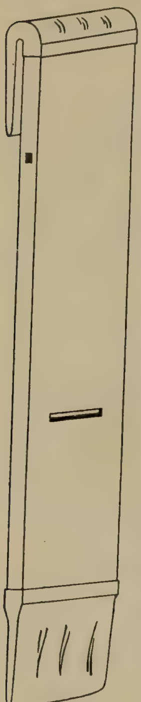


Fig. 13.—Plate-holder for Falling-plate Method.

By the falling plate camera, a record of the current can only be obtained for a very short space of time. This is sufficient in a large number of cases where the current variations are repeated periodically. In other cases, however, where it is necessary to observe a current variation over a long length of time, the principle of fig. 10, *b* must be resorted to, and a curve obtained on a long sheet of cinematograph film or a roll of sensitized paper. A paper camera

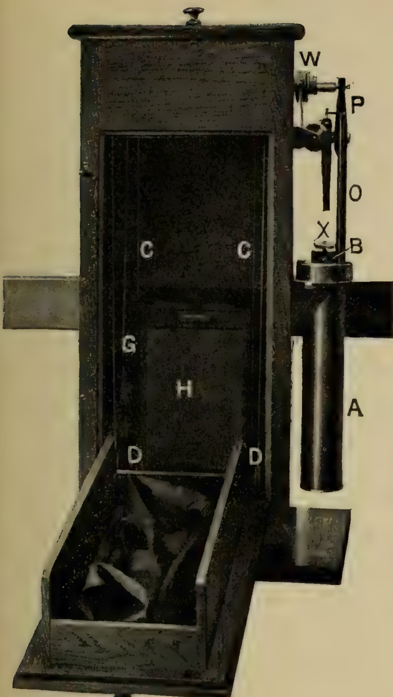


Fig. 14.—Falling Plate with Adjustable Speed.

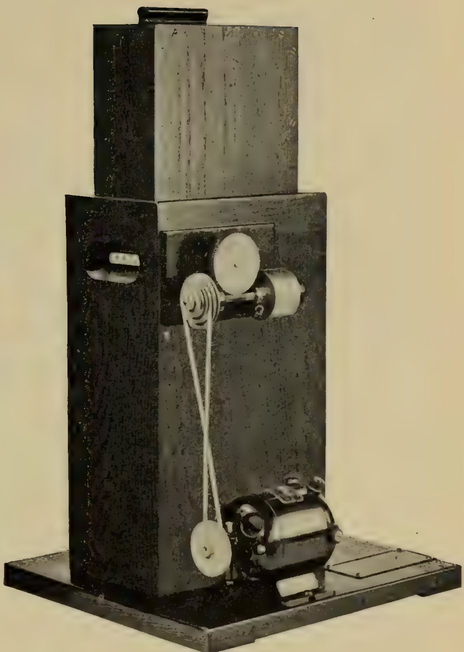


Fig. 15.—Drum Holder for Film or Sensitized Paper Strip moving at Uniform Speed.

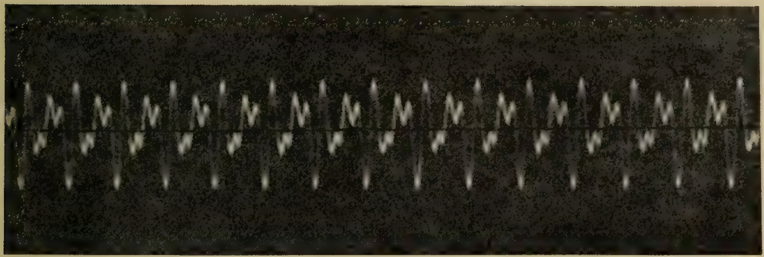


Fig. 16.—Telephone Current Record, Vowel "o" in "Ho"

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for this purpose, designed by the Cambridge Instrument Company, is shown in fig. 15 (see plate). Similar cameras for films may also be obtained. Rolls of bromide paper about 50 yards in length are employed, the paper being made to travel past the slit by means of an electrically driven friction roller, and then fed into a box in which it can be removed for developing. The paper can be driven at various speeds by an electric motor, which in some cases is mounted on a standard suspended from springs, to prevent vibration being transmitted to the camera. In fig. 16 (see plate) the variations of current in a telephone circuit when the vowel "o" is being pronounced are shown. These variations are of very high frequency, and though the example shown has been obtained by the oscillograph, such vibrations can usually be reproduced with greater accuracy by another instrument known as the string galvanometer. As the optical system required for the string galvanometer is somewhat different to that previously described, it is worthy of further consideration.

Fig. 17.—String Galvanometer.

The string galvanometer is actuated on the same principle as the oscillograph, but consists only of a single fibre, usually of silvered glass, passing between the poles of a powerful electro-magnet (fig. 17). When a current passes through the fibre, the latter moves forward or backward according to the direction of the

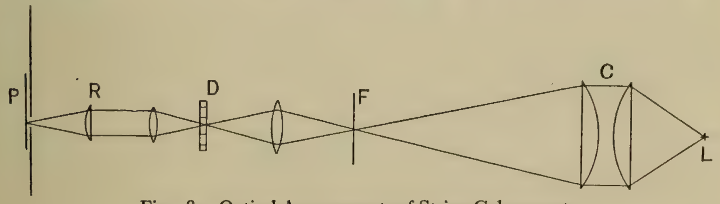

Fig. 18.—Optical Arrangements of String Galvanometer

current, and the movement may be observed through holes bored in the poles of the magnet. By using an extremely light fibre under tension and having no mirror (which would considerably increase the inertia of the system), very weak currents altering with great rapidity may be accurately followed by the fibre and recorded. The record of the deflections is obtained by illuminating a portion of the fibre through the hole in one pole, and obtaining an image on the photographic plate or film. The nature of the optical arrangement is shown in fig. 18. The fibre F is illuminated from the arc of a Pointolite lamp L, or the positive crater of an arc lantern, the

light being concentrated by condensers C. The beam is projected on to a cylindrical prism R in front of the camera, which focuses part of this into an intensely bright horizontal band of light in the plane of the plate or film P. The fibre appears as a dark spot crossing the band vertically. The movements of the fibre are in a direction parallel to the length of the prism and of the band of light, and the instantaneous position of the fibre is indicated by an unexposed spot. If the plate is in motion vertically, the whole in turn is exposed to the photographic effect of the band of light with the exception of that covered by the dark spot. A continuous record of the position of the spot is thus obtained. In conjunction with this instrument, a method of marking a time scale different to that previously described is usually used. This consists of a rotating disc shown at D in fig. 18, which has a number of teeth projecting and cutting off the light at regular intervals as it rotates. The disc is kept in rotation at a constant speed by means of a synchronous motor, operated either by a tuning-fork or by a spring, and thus the distances between unexposed horizontal lines, produced on the plate at each cutting off of the light, represent equal intervals of time. An example of the records obtained with a cinematograph film camera using the tooth-wheel time-marker is shown in fig. 19 (see plate). This is a reproduction of a film obtained with a galvanometer having six independent strings between the poles of the electro-magnet for recording six independent microphone currents, used in sound-ranging both on land and through the sea in the recent war.

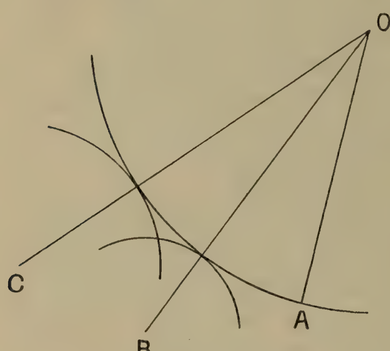

Fig. 20.—Sound-ranging

From a knowledge of the velocity of sound, it is possible to obtain the position of a hidden source by noting the times at which the sound was received at three receiving stations. Let the sound be received at A, B, and C (fig. 20) at times t_1, t_2, and t_3. With B as centre draw a circle of radius $(t_2 - t_1)v$, and with C as centre draw a circle of radius $(t_3 - t_1)v$, where v is the velocity of sound in air or sea water as the case may be. Then the centre O of the circle which passes through A and is tangential to the two other

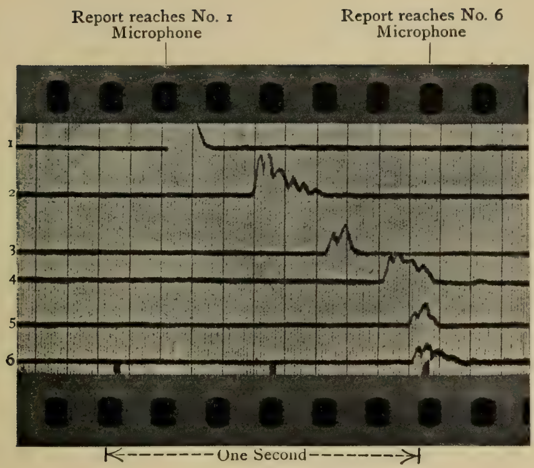

Fig. 19.—Time of Reception of Sound at Six Stations, from which position of Origin of Sound can be found

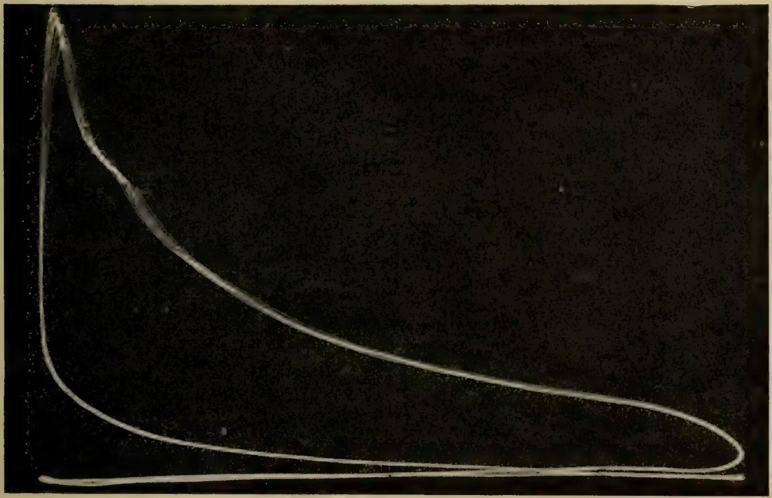

Fig. 23.—Indicator Diagram of Internal-combustion Engine

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circles, will be the position of the source of sound, for the distances of the three stations from O are such that the sound will reach B and C at times $(t_2 - t_1)$ and $(t_3 - t_1)$ respectively after it has reached A. If the sound is in a direction not far from the line joining two of the stations, this construction would not give a very accurate result. For this reason and also because the receiving microphone at one or more of the stations may be put out of action accidentally or otherwise, microphones are laid at six positions, and the currents arising from the impact of the sound on them are led to a six-string galvanometer. By noting the times at which these microphone currents commence and by combining the records from various sets of three microphones, a number of determinations of the position of the source of sound can be obtained. In connection with these instruments, an automatic developing machine has been devised

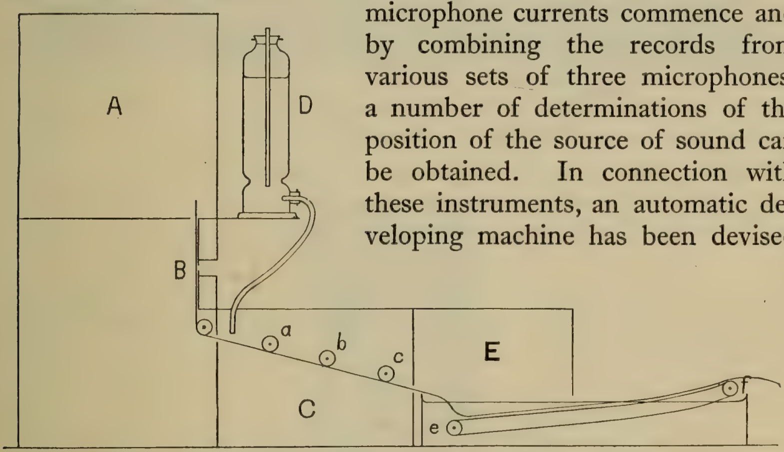


Fig. 21.—Automatic Developing Machine for Films and Paper Strip

in conjunction with the camera, which enables the film or paper to be examined within less than a minute after exposure. The reel is contained in the box A (fig. 21), from which it is fed past the slit B, where the exposure takes place, by means of an electric motor behind the box, which also operates the other moving parts of the machine. After passing the slit, the film passes into the light-tight box C, just within which concentrated developer is dropped on to it from the vessel D. The developer is spread over the film by the rollers *a*, *b*, and *c*, and development is complete by the time the film passes out of C into E, where it drops into a trough of fixing solution. The film is carried through the fixing solution along an endless band of fabric, kept in motion by the rollers *e* and *f* at its ends, and when the film emerges into the open the operation is complete and the record is ready for examination and measurement.

In cases where the motion to be examined is periodic, i.e. it

repeats itself regularly at equal intervals of time, another method is available by which the curves can be examined visually before a photograph is taken. As examples of this, the current variations in a dynamo or motor repeat themselves at least once every revolution, and the pressures in the cylinder of steam-engines and petrol-engines repeat themselves every one and two revolutions respectively. We will consider in turn a couple of examples. If an alternating current is passed through the oscillograph giving the beam of light from the mirror a vibratory motion in a horizontal plane, the time axis may be produced by giving the beam also a vertical vibratory motion, the photographic plate which receives it remaining stationary. The light from the oscillograph mirror is received on a second mirror oscillated by a small electric motor fed by alternating current from the same source as that which is passing through the oscillograph and in synchronism therewith. The

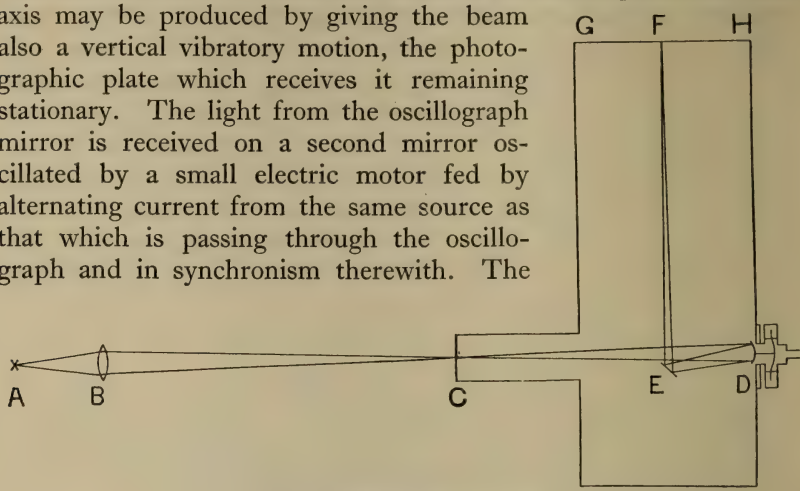


Fig. 22.—Optical Pressure Indicator

spot of light has thus a vertical motion of the same period as its horizontal motion, and passes repeatedly over the same path. By the persistency of vision it can be seen by eye, or can be photographed on the plate. The second mirror may be oscillated by a cam on the shaft of the motor, so shaped that the deflections in the vertical direction are proportional to the time.

The principle of the optical pressure indicator is shown in fig. 22. The light from an arc light A passes through a lens B, which forms an image on a small hole C. The light which passes through falls on a concave mirror D which is oscillated about an axis in the plane of the paper by the pressure exerted in the engine cylinder. The light after reflection is received by the mirror E, inclined at 45°, and finally forms an image of the small hole at F on a ground-glass screen or photographic plate. The oscillations of D would produce on the plate a straight line perpendicular to the plane of

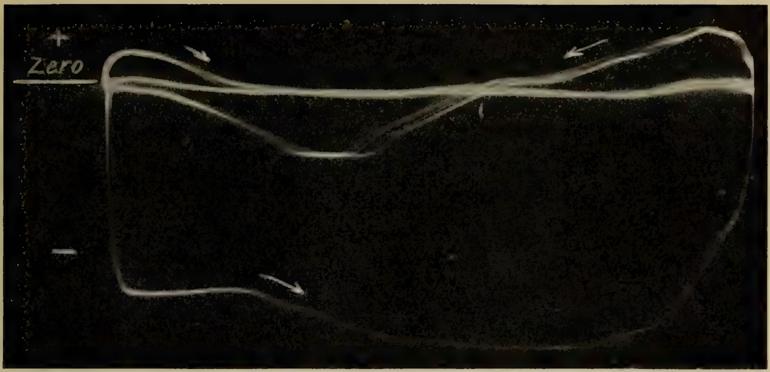


Fig. 24.—Pressure Variation at a Point in a Pipe through which an Intermittent Flow of Air was passing

Fig. 27*b*.—Radiograph of Aeroplane Hollow "Box" Strut, showing badly fitting internal end-block split by screws. (By permission of G. W. Kaye.)

Facing p. 274

the paper with deflection proportional to the pressure. The mirror E, however, is also oscillated about an axis perpendicular to the plane of the paper, by a connecting rod and eccentric rotating at the same speed as the engine, and giving a motion of F along GH which exactly reproduces the piston motion. A diagram of which fig. 23 (see plate facing p. 272) is an example is thus produced, in which the abscissæ represent the position of the piston, and the ordinates the pressure on the piston. The area thus gives the work done per cycle per square centimetre of piston for the cylinder under test, and from this, together with the area and revolutions per minute, the indicated horse-power of the engine can be obtained. The example reproduced is the indicator diagram of a Daimler single-cylinder sleeve-valve engine working at 950 revolutions per minute. The diagram is examined visually on the ground-glass screen until it is seen that the engine is working as desired. The orifice C is then covered while the ground glass is replaced by a slide carrier and the plate exposed, when C is uncovered for a short period. It is again covered while the slide carrier is closed and the plate removed. The plate is usually exposed for a time sufficient to take three or four cycles, as they do not exactly repeat themselves, and an average is desired. Imperial special rapid plates are very suitable for this work, and they should be developed by black-toned lantern-slide developer in order to obtain sharp contrast and clear lines. The same apparatus may be used for obtaining the variation in pressure at any point where it varies periodically. In fig. 24 (see plate) is shown the curve obtained for the pressure at a point in a pipe through which air was being sucked intermittently, the flow being regulated by a valve which opened and closed 500 times each minute. The mirror E (fig. 22) was oscillated by the same shaft that operated the valve, but at twice the speed. Hence the light passed across the plate twice in each direction during a cycle between one opening of the valve and the next. As the motion of the spot is slower at the end of the diagrams than in the middle, the diagram can be placed on a time basis by slowly turning the shaft by hand (the mirror D being stationary), and noting its position for (say) every 15° of revolution. The horizontal intervals between these positions thus represent equal intervals of time. Fig. 25 shows the preceding diagram thus developed, and it will be seen that when the valve closed, the sudden stopping of the incoming air caused the pressure to change from negative to positive, and that there were several

oscillations of pressure before the air within the pipe came to rest.

X-Rays and Conduction through Gases.—In the study of these subjects, which have developed so enormously in recent years, the application of photography in many branches has been of extreme value. When a discharge of electricity is passed through a tube containing gas at a very small pressure (fig. 26) by means of an anode A and a cathode C, rays consisting of negatively electrified particles

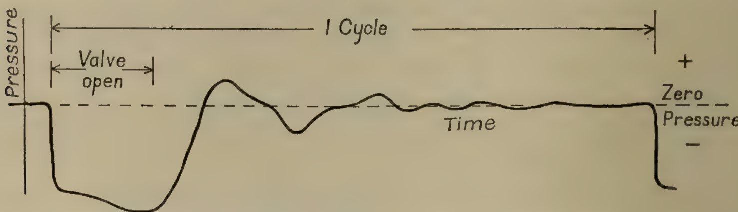


Fig. 25.—Pressure Diagram for Intermittent Air-flow in a Pipe

are expelled from the neighbourhood of the cathode, while positive rays travel in the opposite direction. An electrically neutral atom is now supposed to consist of a central nucleus of small dimensions in which practically the whole mass resides. This nucleus is positively charged, and surrounding it are sufficient negative electrons to make the system neutral. Negative electrons freed from atoms form cathode rays, while the rest of the atom forms the positive particle in positive rays. The β rays from radio-active substances are also

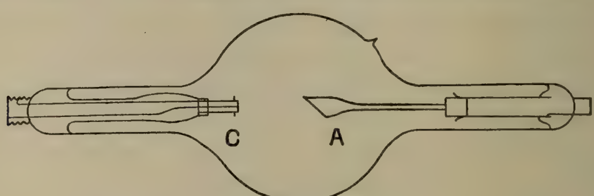


Fig. 26.—Coolidge X-Ray Tube

negative electrons, while α rays are positive helium particles. The nature of negative electrons is the same for all atoms, but the properties of the atoms and of positive particles differ owing to the variation in the number and arrangement of the electrons they contain.

When cathode rays strike upon matter, in addition to inducing phosphorescence and raising the temperature, Röntgen or X-rays are produced. In the form of bulb shown, the anode A serves as an anti-cathode to receive the cathode rays, and from it the X-rays are projected laterally. These rays have been shown to be waves

Fig. 27*a*.—X-Ray Photograph of a Young Frog

Facing p. 276

such as those of light, but of extremely short wave-length. They can be detected by their action on a photographic plate or fluorescent screen. They have the property of penetrating substances, varying in degree according to the nature of the substance. The applications of this property are now extremely numerous, the most important being in the examination of the human body in surgical cases. They are also used to detect flaws in castings and other metallic structures, to examine the soundness of timber, to detect imitation "old masters" and jewellery, to examine oysters for pearls, and parcels passing through the customs office. For visual examination a screen of parchment coated with fine crystals of alkaline platino-cyanide, zinc sulphate, or calcium tungstate is used. These crystals fluoresce where the rays strike them, while the parts protected by opaque matter are shown as a shadow. For permanent records, the ordinary photographic plate has the disadvantage of requiring a long exposure. Only a fraction of 1 per cent of the rays is effective in producing an impression, and the impression is confined to the surface layer of the emulsion. Some improvement can be made by the use of special plates in which the emulsion is thickened with silver and other heavy metals, but for quicker work a fluorescent screen of calcium tungstate is placed in close contact with the photographic emulsion. The screen is caused to fluoresce by the action of the X-rays and the fluorescent light acts on the plate. With such an intensifying screen, the necessary time of exposure is reduced to about one-fifth of the time required without the screen. More recently, a plate has been devised consisting of a film of photographic emulsion, with a second very thin film containing calcium tungstate laid over it. The action is the same as with the ordinary intensifying screen, but it is claimed that the time of exposure required is only one-twentieth of that for the film without screen, and that the picture obtained shows less "grain" than those with the ordinary screen. The film of calcium tungstate is washed off before development of the plate. A form of film known as "duplitized" films, which are constructed of films of gelatine coated on each side with emulsion, are also found much quicker in action than the ordinary photographic plate. By the use of these special means and with X-ray tubes requiring a very large amount of energy, "instantaneous" X-ray photographs can be obtained. Fig. 27*a* (see plate) is a photograph taken with the modern form of tube shown in fig. 26—the Coolidge tube—showing the structure of a young frog. For radiological examination of metals and hard substances,

special precautions have to be taken, as the impact of the rays on hard bodies causes the formation of secondary radiation which fogs the plate. The specimens are therefore embedded in wax and placed as near as possible to the plates. Fig. 27*b* (see plate facing p. 274) is a radiograph of a hollow "box" strut of an aeroplane, taken by Drs. Kaye and Knox,[1] and shows the badly fitting internal end-block, which has also been split by the screws.

The character of X-rays was a matter of controversy for a long period, but was finally decided by the discovery that they could be diffracted by passage through or reflection from the surface of a crystal, whose regular arrangement of molecules acts as a very fine diffraction grating. No diffraction can be found by an ordinary

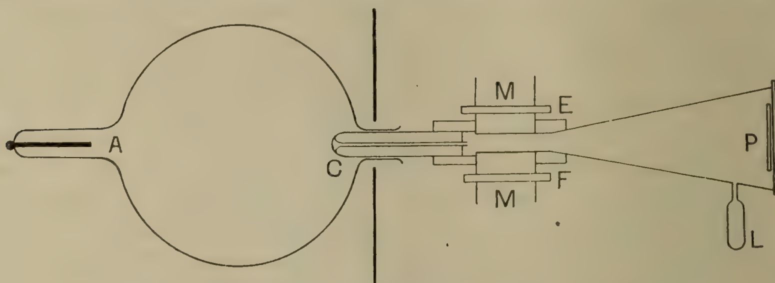


Fig. 29.—Apparatus for producing Deflection in Path of Positive Rays

ruled grating owing to the very short wave-length of the rays. Only a small proportion of the rays is diffracted, and a long time of exposure is necessary to obtain an impression on a plate. In fig. 28 (see plate) is shown the diffraction pattern obtained by Professor Sir W. H. Bragg with a crystal of beryl.[2]

A study of the properties of positive rays has led to a revision of all our ideas of molecular constitution. These rays also act on the fluorescent screen and on the photographic plate. They are deflected by electrical and magnetic fields, and from a study of these deflections the mass of the positive particle and the charge carried can be estimated. The deflections are best studied by receiving the rays on the photographic plate, on which the impression can be examined and measured at leisure. The form of apparatus used is shown in fig. 29. The anode is represented by A and the cathode by C, the latter consisting of a metallic tube of very fine bore down which a fine pencil of positive rays passes. The

[1] *Journal of the Röntgen Society*, 1920.
[2] *X-rays and Crystal Structure*, by Professors Sir W. H. Bragg and W. L. Bragg.

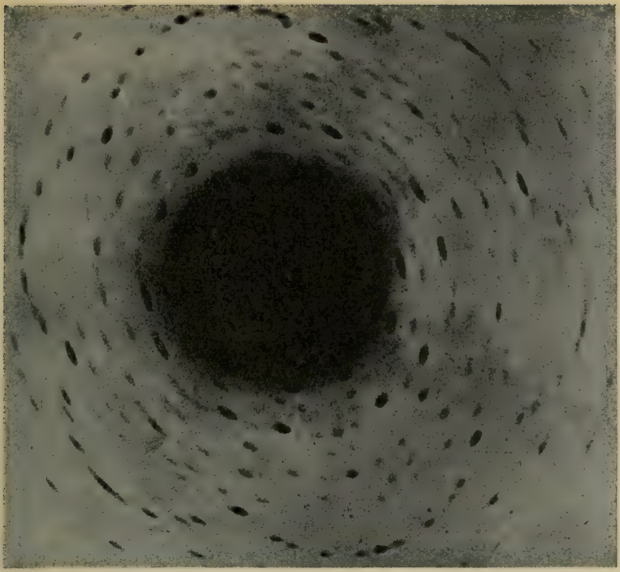


Fig. 28.—Diffraction of X-Rays by a Crystal of Beryl
(From *X-Rays and Crystal Structure*, Sir W. H. and W. L. Bragg)

Fig. 31.—Positive Ray Photograph
by Paget Process Plate
(From *Engineering*)

Fig. 32—Positive Ray Photograph
by Schumann Plate
(From *Engineering*)

Facing p. 278

magnetic and electric fields are applied by the electromagnet M and the electrically charged plates E and F, and after the deflection the rays are received on the plate P. The space between C and P must be in condition of very high vacuo, in order that the rays may pass without interaction between themselves and the gas therein. The pressure in the bulb AC, however, must not be too low or no discharge will take place. The two states are ensured by the use of the very narrow tube, and as the gas slowly passes down, owing to the difference in pressure, it is absorbed by the charcoal contained in the tube L which is immersed in liquid air. Owing to their different velocities, a ray whose particles are of the same mass is spread out and traces a parabola on the photographic plate. Where particles of different mass or carrying different electric charges are present, there are several corresponding parabolas. One method of exposing the plate without disturbing the electrical arrangement is shown in fig. 30. The bulb is shaped at the end in the form of a long cylinder S containing a thin metal box B, within which the plate can slide. Opposite the cathode, at D, the back and front of the box are cut away so that the rays can pass through and be received behind on a "willemite" screen for visual examination. Willemite is a mineral silicate of zinc which is finely ground and deposited on glass, and which fluoresces under the action of the rays. The plate hangs in the upper part of the box from a string which is attached to and wrapped round the tap T, and when the willemite screen shows that the arrangement is in the required condition, the plate can be lowered by turning the tap. The plate is sufficiently long to give two or more exposures, space being provided below the aperture D to receive the lower and exposed part of the plate while the upper part is being exposed. As in the case of X-rays, only a very thin surface film of the plate is affected by the rays owing to absorption by the gelatine, and it is possible to wash away all traces of the rays by immersing the undeveloped plate in water and brushing it with a camel-hair brush. The necessary requisite in a plate is a very thin film of emulsion with a large amount of silver in it. The most rapid plates are not necessarily the most sensitive for this purpose. The same difficulty is experienced in

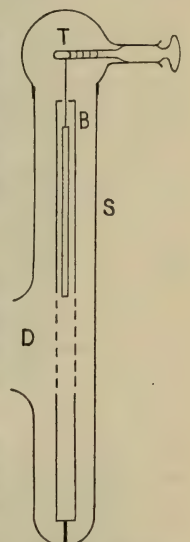


Fig. 30.—Method of Exposing Plate (Positive-ray Photography).

the photography of ultra-violet light in spectroscopy, which is similarly absorbed by gelatine, and special plates, known as Schumann plates after their inventor, have been made for such work. These have a very thin film of silver bromide bound together with very little gelatine. Details of the exact method of manufacture will be found in Baly's *Spectroscopy*. Certain types of ordinary commercial plates, however, produce satisfactory results with suitable exposure. A photograph taken with a Paget Process plate is shown in fig. 31 (facing p. 278) and another under exactly the same conditions with a Schumann plate is shown in fig. 32 (facing p. 278). Owing to its finer grain the former gives a more well-defined image, though not so intense as the latter. Imperial Sovereign plates may also be used with success. The relative intensities of the lines are no indication of the number of particles which have been received by the plate, as particles of different kind affect the plate to very different degree, and the relative number can only be found by electrical measurements.

When α or β rays of radio-active substances or cathode, positive, or X-rays from the discharge tube, pass through a gas they ionize the gas, i.e. they separate one or more negative electrons from some of the atoms or molecules through which they pass. This property has been used to make visible and to photograph the path of the rays. If a gas is saturated with water vapour and then cooled, a portion of the vapour will condense as a cloud on dust particles which are usually present scattered throughout the gas. If the dust particles are all removed, the water will not condense in gas consisting of neutral atoms or molecules, but will do so on electrons. By obtaining an estimate of the number of drops of water formed, C. T. R. Wilson has thus been able to obtain the number of ions in a given space. Further, if a beam of X-rays or radio-active rays is passed into a space containing gas supersaturated with water vapour, but previously containing neither ions nor dust particles, the action of the rays in producing ions will cause a trail of water drops to form, marking out the path of the rays, and photographs can be taken of these trails of water drops. The photographs are obtained by spark photography in the manner described at the beginning of this chapter. The cooling of the gas is produced by a sudden increase in the volume of the containing chamber, necessitating sudden expansion of the gas. In the case of rays from radio-active substances, a shutter may be operated by the same string which produces the expansion, the shutter being arranged so that the rays can pass through the gas for a brief

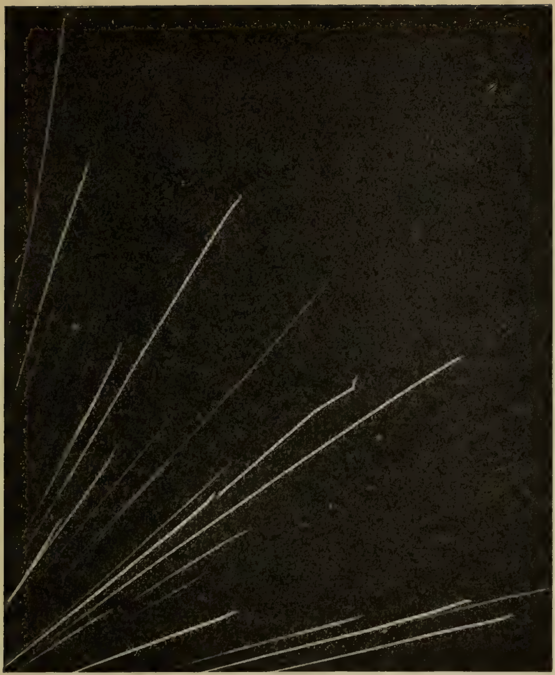
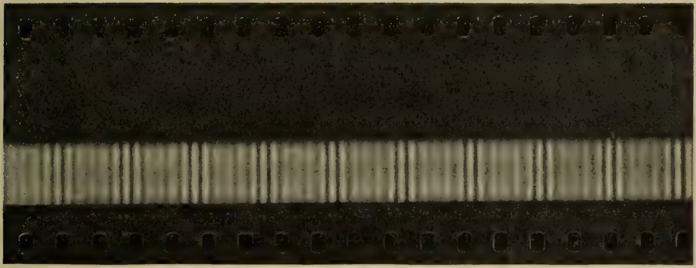
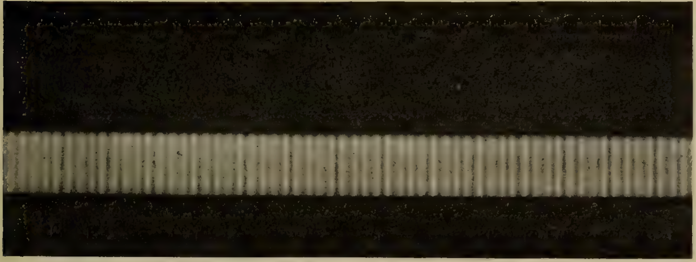


Fig. 33.—Tracks of α Particles by C. T. R. Wilson
(From Proceedings of the Royal Society)



(*a*) Frequency of Note, 135 per second



(*b*) Frequency of Note, 205 per second

Fig. 35.—Record of Vowel "ah" by Prof. A. O. Rankine

Facing p. 280

interval shortly after the expansion. Also attached to the string is a heavy ball which falls between a spark gap of an electrical condenser circuit, and, closing that gap, produces a bright spark discharge at a second gap after another brief interval following the passage of the rays. The photograph of the drops is taken by the illumination of the spark discharge. In the case of ionization by X-rays, the falling ball first closes a circuit which produces a momentary discharge through an X-ray tube, and then farther in its fall closes the second circuit and produces the illumination spark. An instantaneous photograph showing the water particles on the ions due to the passage of α rays from radium is reproduced in fig. 33 (see

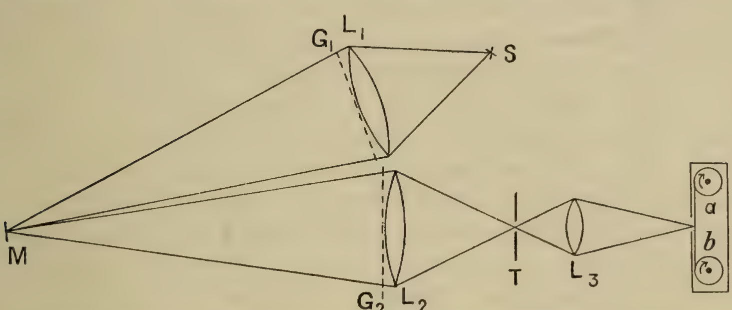


Fig. 34.—Professor Rankine's Apparatus for Recording and Reproducing Sounds Photographically

plate).[1] A Beck " isostigmar " lens with full aperture was used and Ilford Monarch plates.

Miscellaneous.—In addition to the examples already given, there are many others in which variations of the methods described are used. In Heat, a continuous record of the temperature of a furnace or other body may be obtained by the use of a thermocouple or platinum resistance thermometer, the recording instrument consisting of a galvanometer whose deflections are proportional to the temperature and are recorded on a moving film or photographic paper. In Sound, the records of telephone currents have already been mentioned. Another very interesting example in Sound of an entirely different nature is furnished by the recent experiments of Professor Rankine on the recording and reproduction of sounds by a photographic film.[2] The arrangement is shown diagrammatically in fig. 34. The rays from a Pointolite lamp S are focused by a lens L_1 on to the concave mirror M, which is in connection with the diaphragm of a gramophone, and is oscillated

[1] *Proc. Roy. Soc.*, Vol. A, 87. [2] *Proc. Phys. Soc.*, Vol. XXXII.

by the vibrations of the diaphragm. The rays of light after reflection are concentrated by the lens L_2 on to the slit T. An image of the slit T is then obtained by the lens L_3 on a cinematograph film in motion round the pulleys *a* and *b*. In front of the two lenses L_1 and L_2 are two grids G_1 and G_2, consisting of sheets of metal cut out so as to form parallel strips alternated with slits of equal width. The distance between each of them and the mirror M is equal to the radius of curvature of M, so that the image of G_1 is formed at G_2. If, when the mirror is stationary, the image of the slits of G_1 coincide with the slits of G_2, the full light passes through and is concentrated on to T. When M is caused to oscillate by the impact of sound on the diaphragm, the image of G_1 is in rapid vibration, and the intensity of the light passing through G_2 depends on the amount of overlapping of the image of the slits of G_1 with the slits of G_2. The intensity of the light illuminating T thus varies rapidly, and consequently the density of the image on the film undergoes similar variation. In practice, it is found better to adjust the mirror so that the images of the edges of G_1 are in the centre of the slits and strips of G_2. With this arrangement only half the light is transmitted for the position of rest, but movement of the gramophone diaphragm in opposite directions is shown by increase and decrease of light respectively, whereas both movements would give a decrease with the other arrangement. Furthermore, the effect of irregular edges or slight lack of parallelism is by this means eliminated. The character of the variations in intensity is determined by the nature of the sound impinging on the gramophone and causing M to oscillate, and it is hoped the study of the records will furnish valuable information in the study of phonetics. Two simple records are shown in fig. 35 (facing p. 280). Both examples were obtained by speaking the vowel "ah" into the gramophone, but in one case the voice was pitched to a note of frequency 135 per second and in the other to a higher pitch of 205 per second. The velocity of the film was a little over a metre per second, and it will be seen that whereas, in the record of the vowel spoken to a low pitch, the fundamental frequency is represented by bands about 8 mm. apart which are much more intense than the others, in the records obtained at a higher pitch the importance of the fundamental is much less prominent, and sound variations of almost equal intensity are obtained of much higher frequency. Records of words are much more complicated than the vowel records shown. These records can be used to reproduce the sound by which

they have been made. An image of an illuminated slit is produced on the film, and the light passes through the film and is received on a selenium cell through which a current of electricity is passing. As the film is moved, the intensity of the light transmitted varies inversely as the density of the film, that is, inversely as the light which originally fell on the film. The light falling on the selenium cell alters its electrical resistance and hence also the current passing through it. If a telephone receiver is included in the circuit, the variations of current reproduce the sound in the same way as the variations of current produced in the ordinary manner by a telephone transmitter.

One of the most important and extensive cases of the use of photography in physics is in the branch of Light dealing with spectrography, but as this is allied with astro-physics it is included in the chapter on astronomy. Another case which may be mentioned is

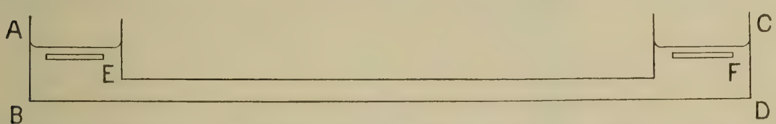


Fig. 36.—Apparatus used in Measurements of the Rigidity of the Earth by Prof. A. A. Michelson

the recent work of Professor Michelson, who has used the photography of interference bands produced by reflections at the surface of a thin film, to obtain a continuous record of its thickness. The work occurred in a redetermination of the rigidity of the earth.[1] In fig. 36 ABCD represents a U tube filled with water and fixed below the surface of the earth to avoid temperature variations. As the shape of the earth alters due to lunar and solar attraction, the tube will remain parallel to the surface at the point where it is fixed, but the level of the water will always be perpendicular to the line joining the apparatus to the centre of the earth. If E and F are two plates of optically worked glass, fixed relative to the apparatus, the film of water above one will increase and that above the other will decrease, and vice versa, during the periodic changes, and a measurement of the varying thickness of the films will give the angular movement of the surface of the earth relative to the line joining it to the centre. A continuous photographic record of the interference bands was obtained for an entire year on a slowly moving cinematograph film, and the change in shape of the earth indicated by the displacement of the bands showed that the earth had a rigidity equal to that of steel.

[1] *Proc. Phys. Soc.*, Vol. XXXIII.

CHAPTER VII

Photography in the Engineering and Metallurgical Industries

The value of the camera has been increasingly recognized year by year in the metallurgical and engineering industries during the last quarter of a century. Probably one of the earliest uses of photography in these industries was in connection with the microscope, and at the present time it is as frequently used for this purpose as for any other. There are now few laboratories in metallurgical or engineering works which are not equipped with a photomicroscope. In this chapter the methods of photomicrography as applied to metals will first be briefly described, and afterwards a short account will be given of the application of photographic methods to other purposes. It is not intended to describe the " blue print " or other similar methods used in drawing offices for copying drawings.

Photomicrography

It is assumed that the reader who wishes to use the photomicroscope for metallurgical work is familiar with the type of microscope required for metal sections. It may be useful, however, to note the essential characteristics of such a microscope, and also the features desirable in one to be used for photomicrography.

Metal sections, being opaque, require lighting arrangements differing from those found in microscopes used with transparent sections. It is necessary to use light reflected from the surface of the section, and in order to do this a vertical illuminator is employed. The stage should be fitted with a coarse focusing adjustment in order to avoid disarranging the lighting arrangements by the movement of the microscope tube. It is desirable, especially for photomicrographical purposes, that the range of the focusing adjustment

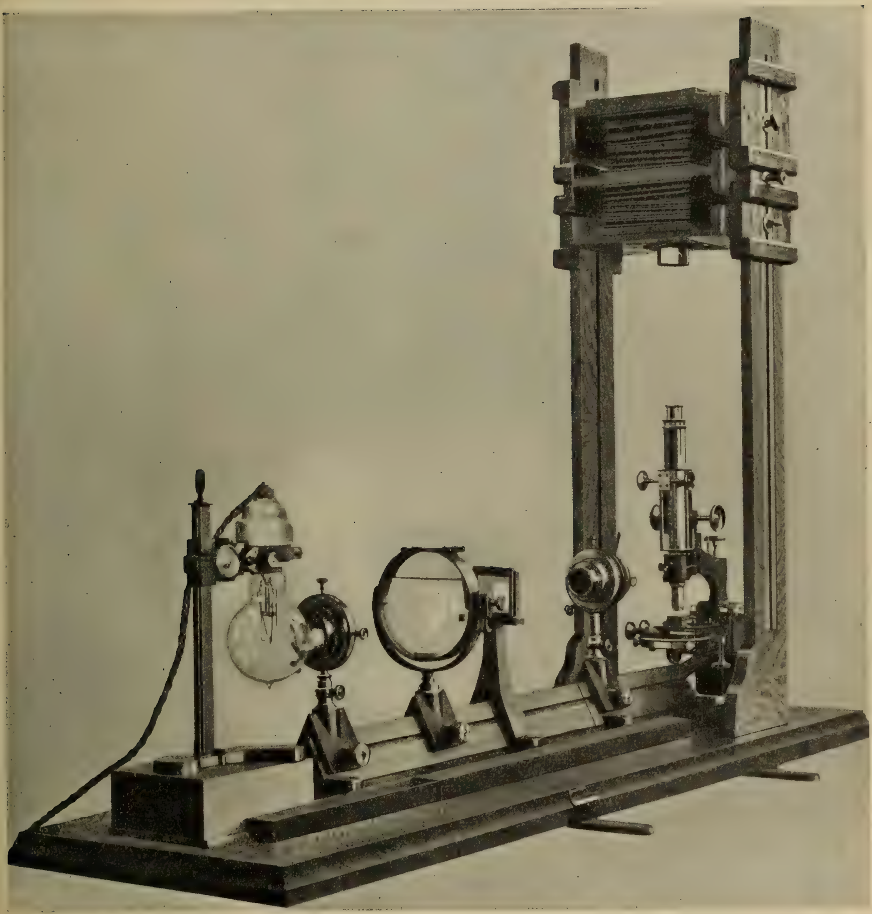


Fig. 1.—Photomicroscope used by the Author for Metallurgical Work

Facing p. 284

fitted to the stage should be sufficient not only to take care of varying thicknesses of specimens, but also for the adjustments required on changing from the lowest to the highest powers. The body tube of the microscope should be of large diameter; this is especially desirable for low-power photography, as will be seen later, while it also permits the use of a vertical illuminator of ample size.

One of the most essential conditions for photomicrography is the absence of vibration, or at any rate of relative movement of the different parts of the photomicroscope. The best way to ensure this is to have the different parts of the apparatus, camera, microscope, and illuminating system, firmly fixed to a solid base-board. The author is aware that in at least one notable design of apparatus, the Zeiss, the camera and microscope are on separate tables, but with this arrangement a solid floor is absolutely essential, or, if this is not obtainable, both parts of the apparatus must be supported on a heavy base-plate which in turn is supported by some type of anti-vibration stand. Such an arrangement is, to all intents and purposes, the same as having the apparatus fixed to one base-board.

The photomicroscope used by the author is shown in fig. 1 (see plate). It will be noticed that the microscope tube and the camera are vertical. In metallurgical work this form is preferable, in the author's opinion, to the horizontal form generally used with transparent sections. With the vertical form, the mounting of sections of large size and weight, such as often occur in works' laboratories, is easily done by embedding in plasticine. With the horizontal position of stand and camera, the stage is vertical and heavy sections require to be embedded in sealing-wax or similar hard media to prevent movement. In addition, the stage springs have also to be very strong to prevent the specimen sagging forward. There is also danger of the mechanical stage moving downwards. On the other hand, with the vertical form it is possible that the focusing adjustments may move slightly during exposure, especially if there is any backlash in the movement. A great deal of this difficulty, which only arises at the highest powers, may be avoided, however, by approaching the final focus by raising the objective instead of lowering it.

A further point of superiority of the vertical form may be mentioned. It is much easier to arrange the section under the microscope and to make adjustments to the illumination while looking down the microscope in the ordinary way than by examining an image projected on a screen. With the vertical form, the camera

is simply pushed to the top of the slides, and there is ample room for the head between the latter. In the horizontal pattern, the base-board is in the way and one has either to crane one's neck over this or else have the microscope and illuminating system mounted on a turntable which can be rotated, allowing the microscope, &c., to be turned out of line with the camera. Such an arrangement is frequently employed in photomicroscopes for use with transparent sections, but is very cumbersome in a metallurgical apparatus where the condensing system is arranged at right angles to the optical axis of the microscope.

The most convenient size for the camera is half-plate. In most cases a quarter-plate negative is sufficiently large, but for low-power work the half-plate size is frequently necessary. The half-plate dark slides should be fitted with quarter-plate carriers.

The camera should be capable of extending 20 to 30 in. As a general rule there is rarely any need for more than 20-in. extension, except in low-power work when an objective is frequently used without an eye-piece. In this case more than 20 in. may be necessary, e.g. a 35-mm. projection lens at 20 diameters (a useful figure) requires a camera extension of about 28 in., of which the microscope tube will account for 4 or 5 in.

Objectives.—Probably the lenses most used for metallurgical work are those of 24 mm. (or 16 mm.) and 4 mm. focal length. The former has generally a numerical aperture of 0·25 to 0·3, and is used for magnifications of 50 to 150 diameters, while the latter has N.A. 0·8 to 0·9, and gives 400 to 750, or even 1000 diameters. For a great deal of work these two lenses are all that is necessary, and where only a limited sum of money is available they should be obtained. Where greater resolution than that given by the 4-mm. lens is required a 2- or 3-mm. oil-immersion lens working at N.A. 1·3 to 1·4 is necessary. Occasionally the field of the 24- or 16-mm. lens is not sufficiently large for coarse structures, and for these one may use a 35- to 50-mm. ($1\frac{1}{2}$ in. to 2 in.) objective. Magnifications below about 25 diameters are best obtained by special projection objectives or short-focus photographic lenses, the use of which is described later. Occasionally a 12- or 8-mm. ($\frac{1}{2}$ in. or $\frac{1}{3}$ in.) lens of N.A. about 0·6 may prove useful for showing fine structures or small flaws at a magnification of about 250 diameters.

Reference has been made occasionally [1] to the difficulties

[1] H. M. Sayers, "Illumination in Micro-metallurgy", *Trans. Faraday Soc.* Vol. XVI, No. 1, p. 172.

attending the use of a 4-mm. objective. It is stated that with such a lens, the working distance of which is very short, reflection of the light occurs at the front lens of the objective, causing flare to such an extent as to make it impossible to obtain photographs with sufficient contrast, and for this reason a special oil-immersion 4-mm. lens is recommended. The author would say at once that he has never experienced this difficulty. He has used 4-mm. lenses of various numerical apertures and working distances, ranging from the Zeiss 4-mm. apochromat (which has a working distance of 0·2 mm.) to the special low-aperture lens of long working distance, such as the $\frac{1}{6}$-in. parachromatic (N.A. 0·74) made by Watson's, London (which has a working distance of 1 mm.), and has never had the slightest difficulty in easily obtaining all the contrast he required in the photographs obtained with them. For ordinary work in a laboratory, where one often requires to use 24-mm. and 4-mm. lenses in succession on the same field, an oil-immersion 4-mm. would be a nuisance.

Objectives may be divided into two classes, depending on the perfection of their construction:

(*a*) apochromatic,
(*b*) semi-apochromatic and achromatic.

In the achromatic type, which includes the great majority of lenses, the correction for spherical aberration is only carried to anything like perfection for light of one colour, generally yellow-green. Such objectives have also quite a distinct difference in focus with yellow-green light and with blue or red light. They should always be used with a yellow or green filter and orthochromatic plates, as they generally perform very badly with blue or blue-violet light.

Semi-apochromatic lenses are of the achromatic type, but the various corrections are carried to a greater degree of accuracy. Like the achromats, however, the highest degree of correction for spherical aberration is found with light of one colour only (generally yellow-green), and they perform much better with light of this colour than with any other.

With apochromatic lenses the corrections for spherical aberration are taken to a very high degree of perfection for light of all colours, while the differences in chromatic aberration are reduced to a very small amount. These lenses, however, are much more complex than the other types and are necessarily more expensive.

Where work at the highest powers has to be done, necessitating an oil-immersion lens, the author would recommend a 2- or 3-mm. apochromatic objective. It should be remembered in this connection that the capacity of an objective for showing fine detail depends on the wave-length of the light used as well as on the numerical aperture of the objective. Other things being equal, the use of light of wave-length 4500 A.U. instead of 5500 A.U. is equivalent in its effects to an increase in the numerical aperture of about 25 per cent. Hence the capability of the "apo" lens of working with blue-violet light gives it a distinct superiority over the "semi-apo", which works only with yellow-green light. Apart from these disadvantages, many of the semi-apochromat lenses perform extremely well.

The two photographs in fig. 2 (Plate V, p. 523) are magnified 3000 diameters, and were taken respectively with a Zeiss 2-mm. apochromat and a Watson 2-mm. holoscopic objective. As will be seen, the definition of the Watson semi-apochromat compares favourably with that of the Zeiss apochromat.

For the 4-mm. the apochromatic objective is preferable, but very good work can be done with a good semi-apochromatic lens.

As regards the lower-power lenses, 24 or 16 mm. (1 in. or $\frac{2}{3}$ in.), there is probably little to choose between apochromats and semi-apochromats except that the latter must be used with yellow-green light. For most metallurgical sections, however, light of this colour is perfectly suitable, and the use of the semi-apochromat only involves the use of an orthochromatic plate and screen with a rather longer exposure and more care in the dark-room illumination.

Some typical photomicrographs which illustrate the performance of different kinds of objectives are shown in Plates VI (p. 525), VII (p. 527), and VIII (p. 529). The definition obtainable from semi-apochromats and achromats at 750 diameters is shown in fig. 3, B and C, and may be compared with fig. 3, A, taken with a Zeiss apochromat. The value of a 12-mm. lens is indicated in fig. 3, D, and fig. 4, C. Fig. 4, A, B, D, and fig. 5, A, show that, under proper conditions, low-power semi-apochromats give results indistinguishable from those obtained with apochromats. Fig. 5, B, illustrates the use of a 2-in. objective for low magnifications.

Achromatic lenses, especially of the lower powers, have one advantage over apochromats in that their field is much flatter. With all ob-

jectives the projected image is more or less curved, and consequently if the centre of the field is focused the outer parts are more or less out of focus, and vice versa. This roundness of field is especially noticeable with apochromats, so that only a small area in the centre of the field can be obtained sharp all over (generally about $2\frac{1}{2}$ in. diameter at a magnification 8 to 10 times the initial power of the objective). Many achromats, however, especially the lower-power lenses (about 1 in. or $\frac{2}{3}$ in. focal length) have considerably flatter fields, and are exceedingly useful in this respect (see fig. 5, Plate VIII).

All apochromatic objectives and most of the others are designed for use with a definite tube-length, generally 160 or 250 mm. (6 in. or 10 in.), which must be adhered to if the best results are to be obtained. There is no difference in the behaviour of "long" or "short" tube lenses. It may be noted, however, that the tubes of many microscopes cannot be shortened below about 140 mm., and this only allows for a very small size of vertical illuminator if an objective corrected for the 160-mm. tube be used. For this reason the longer tube-length is more convenient metallurgically.

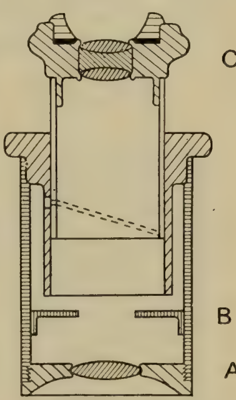


Fig. 6.—Projection Ocular showing Construction

Oculars.—Although the oculars ordinarily used for visual observations may be used for photography, it is better to employ the projection oculars specially made for the purpose. The latter are made in two powers, the lower power magnifying three times on the 250-mm. tube (twice on the 160-mm.) and the other twice as much. Unless a very long camera is to be used the higher-power ocular is the more useful. The construction of these oculars is shown in fig. 6. The objective (together with the field-lens A) produces an image of the object in the plane of the diaphragm B. This image is projected on to the plate by the triple eye-lens C. Obviously if the image produced by the objective is to be formed every time in the plane of B, the position of C must alter with respect to B with every change in the camera-length, since the distance BC and the camera-length are the conjugate foci of C. For this purpose the eye-lens C is mounted in a sliding tube and its position is read off on a scale. For each camera-length, C should be adjusted so that a sharp image of the diaphragm appears on the ground glass.

As the position of the eye-lens depends solely on the camera-length, this position for each length should be determined and a table or graph made so that the eye-piece may be set for any camera-length required.

Projection oculars give a very sharp image but they have a comparatively small field; occasionally with lower-power objectives, especially achromats or semi-apochromats, a somewhat larger field may be obtained by using an ordinary low-power Huyghenian ocular.

It may be pointed out that the effect of using a Huyghenian ocular (or a compensating ocular for that matter) for projecting the image into the camera causes a shortening of the effective tube-length of the microscope, to an amount varying with the ocular but amounting in some cases to 10 to 20 mm. When used visually, the eye-lens of such oculars forms a magnified virtual image of the real image formed by the objective in the plane of the diaphragm, and consequently the eye-lens and diaphragm are much closer together than they would be if the former were projecting a real image of the plane of the diaphragm on to the camera-screen. Since, in the ordinary ocular, the distance between the eye-lens and diaphragm is fixed, the objective image has to be formed farther from the eye-lens (and therefore nearer to the objective than the plane of the diaphragm) when the ocular is used for projection. With a Huyghenian ocular magnifying seven times on a 250-mm. tube, the shortening of the effective tube-length was about 10 mm. when the ocular was used with a camera-extension of 400 mm. Such a shortening would have no effect on a low-power achromat, though it would affect a high-power apochromat.

In addition to this, the corrections for spherical aberration of the ocular are adjusted for its use visually; these corrections may not hold so well when it is used for projection.

The Vertical Illuminator.—Of the two forms in which this is made, the disc and prism, the author unhesitatingly recommends the disc, especially for high powers. In many illuminators, however, the disc is much too thick, causing the definition given by the objective to be affected. Curiously enough, low-power objectives with large back lenses (such as the 1-in. and $\frac{1}{2}$-in.) which utilize a large area of the disc, are affected very much more than high-power lenses such as the $\frac{1}{6}$-in. or $\frac{1}{12}$-in. The effect on low-power lenses is illustrated in fig. 7 (Plate IX, p. 531), A and B, which were taken under identical conditions, except that in A a disc 0·1 mm. thick was

used, and in B one of 0·5 mm. thickness. The thinner disc was an ordinary No. 1 cover-glass; the thicker, a piece of optically worked glass. It will be seen that the definition is absolutely ruined by the thick disc. With a 4-mm. Zeiss apochromat at 750 diameters, the definition with the thick disc was almost as good as with the thin. It is necessary to emphasize the bad effect of the thick disc on low-power lenses, since the opinion appears to be widely held, due no doubt to the much smaller effect on high-power lenses, that a thick disc is quite suitable.

The illuminator should be fitted with an iris diaphragm, and both this and the disc itself should be large enough to illuminate the whole of the back lens of any objective to be used; an opening of 11 mm. in the iris is sufficient. The iris should also have centring adjustments, at any rate in a direction perpendicular to the axis of the microscope. The illuminator used by the author, and preferred by him to any other he has seen, is the Johnson Stoney pattern made by Watson's, London; it is shown in fig. 8. Care should be taken, however, to see that a suitable glass disc is fitted.

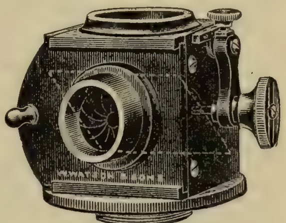


Fig. 8.—Large-size Vertical Illuminator, Johnson Stoney Pattern

One of the defects of the disc illuminator, especially with lower-power objectives, is the presence of flare, due to the reflection up the microscope tube of the incident light by the outer surface of the back combination of the objective. It will be obvious that, other things being equal, the amount of this reflected light which reaches the eye-piece will depend on the radius of curvature of the back lens. The more convex this surface is, the less the amount of reflected light reaching the eye-piece, since more of this light will be reflected on to the inner surface of the draw-tube and be absorbed by the blackened surface. With achromats the back lens is often quite convex, and most of the reflected light reaches the sides of the tube and is absorbed. The back lenses of apochromats, on the contrary, are generally much flatter and hence show a greater amount of flare. This flare, of course, tends to lessen the contrast in the image. This point has been previously noted by the author.[1]

The prism form of illuminator gives, as a general rule, somewhat brighter images than the disc, and is preferred by some metallurgists

[1] *Trans. Faraday Society,* Vol. XVI, No. 1, p. 145.

for low-power work, though probably this preference is due to the use of unsuitable " discs ".

The loss in definition and resolving power which attends the use of the prism illuminator, with high-power objectives especially, has been referred to so often, that it is unnecessary to deal with it. For low powers, however, the loss is not so serious, and the prism is often used on account of its greater contrast-giving properties, which are due to the absence of the flare produced with the disc as described above.

On the other hand, with such low powers, greater difficulty is experienced with the prism in evenly illuminating large fields. The author's preference is certainly for the disc for all powers, and he very rarely uses the prism.

In connection with the prism illuminator, it is curious that, in the pattern as ordinarily sold, the iris diaphragm closes concentrically with the middle of the front face of the prism, and therefore round a line about $\frac{1}{8}$ in. from the centre line of the objective. The iris should, of course, close concentrically with the middle of the bottom edge of the prism, as shown in fig. 9, where A indicates the centre line of the iris as ordinarily fitted, and B the line on which it should close. One of the faults of the prism illuminator is that the light is perforce somewhat oblique. Using the iris in position A accentuates this considerably.

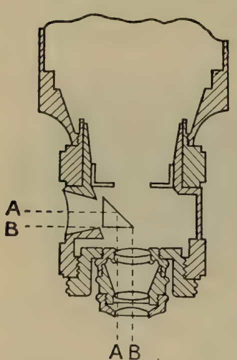


Fig. 9.—Position of Iris Diaphragm on Prism Illuminator.

Illuminant and Condensing System.—Apart from the microscope, the most important part of the photomicroscope is the illuminant and condensing system. For a successful photograph the illumination should fulfil the following conditions:

(*a*) The whole of the field to be reproduced should be evenly illuminated.

(*b*) It should be possible to fill the whole of the back lens of the objective with a uniform beam of light.

(*c*) The wave-length of light used should be that for which the objective is corrected.

Occasionally, when dealing with metals, the colour of the sample may require light of definite colour for the best reproduction; such

cases, however, are exceedingly rare. They are dealt with later under " Colour Screens ".

As regards the illuminant, the author prefers the 500 candle-power Pointolite lamp (a tungsten arc-lamp made by the Edison Swan Electric Co.) to any other type of lamp made. The intensity of the light is very great and it is absolutely steady. It requires direct current, and where this is available the author has no hesitation in recommending its use. The ordinary arc-lamp can be made more powerful but it is not perfectly steady, especially when run on alternating current. For many years the author employed limelight (using an injector-jet) in preference to an arc-lamp or a Nernst lamp. The intensity of the limelight is not so great, but it is quite steady, and for low and medium powers the amount of light is quite sufficient. For the very highest powers the exposure with rather dark sections is rather long (which may cause trouble through vibration), and it may be somewhat difficult to focus owing to the poor light.

In metallurgical work the objective acts as condenser and should focus the illuminant on the section. To do this, the distances x and y in fig. 10 should be equal. With such an arrangement, if the objective is focused on the sample and the eye-piece then removed, the whole of the back lens of the objective will be found to be evenly lit, presuming the opening in the vertical illuminator is large enough. The image of the illuminant, however, becomes visible in the field of view with this arrangement, an obviously undesirable effect. This, however, may be overcome to a great extent by moving the illuminant about an inch or so nearer the microscope than indicated in fig. 10. No bad effect is produced by so doing, providing the objective still transmits a full solid cone of light.

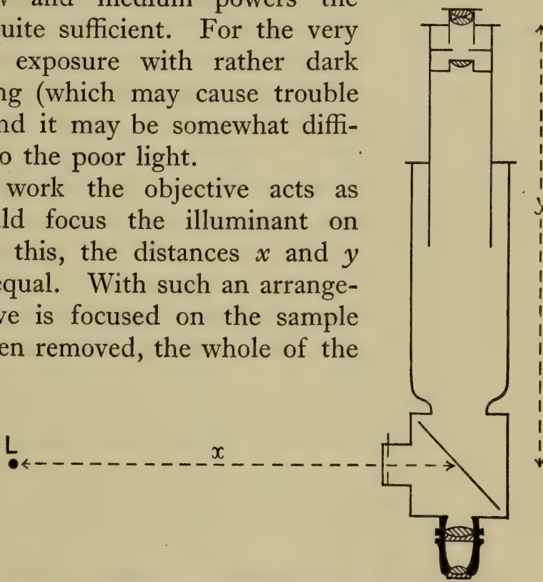


Fig. 10.—Diagram showing Conditions for Critical Illumination

Placing the illuminant in such a position has obvious disadvantages; it would be inconveniently close to the microscope, and the

heating effect on the latter would be considerable. In addition to this, the light would require to have an evenly bright area at least as large as the diaphragm of the ocular in use in order that the field visible in the microscope could be evenly lighted, a condition fulfilled by very few illuminants.

This difficulty may be overcome by having the light some distance, say 30 to 40 in., from the microscope, and placing near to it a short-focus bull's-eye condenser in such a position that it forms an enlarged aerial image of the light in a position corresponding to L in fig. 10. This arrangement is shown in fig. 11. By this means the field of view may be evenly illuminated, but a great deal of light is lost since the beam of light thrown by the bull's-eye condenser diverges after it passes L_1 (fig. 11), and only a small portion of it enters the microscope.

A much more satisfactory illumination may be obtained by proceeding as follows. If a biconvex lens be held between the eye and a candle flame in such a manner that the eye and flame occupy the position of conjugate foci, it will be found that, to the eye, the lens appears to be an even disc of light. Such a disc of light may obviously be used as an "illuminant" for the microscope. Fig. 12 shows the arrangement of condensers utilizing this idea. A represents a lens of about 6 in. focus placed at a position corresponding to L in fig. 10. The objective, therefore, uses this lens as illuminant and forms an image of it in the plane of the section. Condenser B (about $2\frac{5}{8}$ in. focus and $2\frac{1}{8}$ in. diameter) is placed at such a distance from A that the latter focuses B approximately on the objective. Finally B focuses the illuminant L on condenser A. Since A and L occupy positions of conjugate foci with respect to B, the latter appears as an evenly illuminated disc to A; hence the image of B produced on the back of the objective consists of an even disc of light about $\frac{2}{3}$ in. diameter, and therefore amply large enough to fill the whole aperture of any microscopic objective. In the same way condenser B and the objective occupy the positions of conjugate foci of A, and the latter appears to the objective as a uniform disc of light. The objective, therefore, forms an image of this even disc in the plane of the section, which is by this means evenly illuminated.

The dimensions given above refer to the author's apparatus; they may, obviously, be varied to some extent. The points to be watched carefully in arranging such a system are:

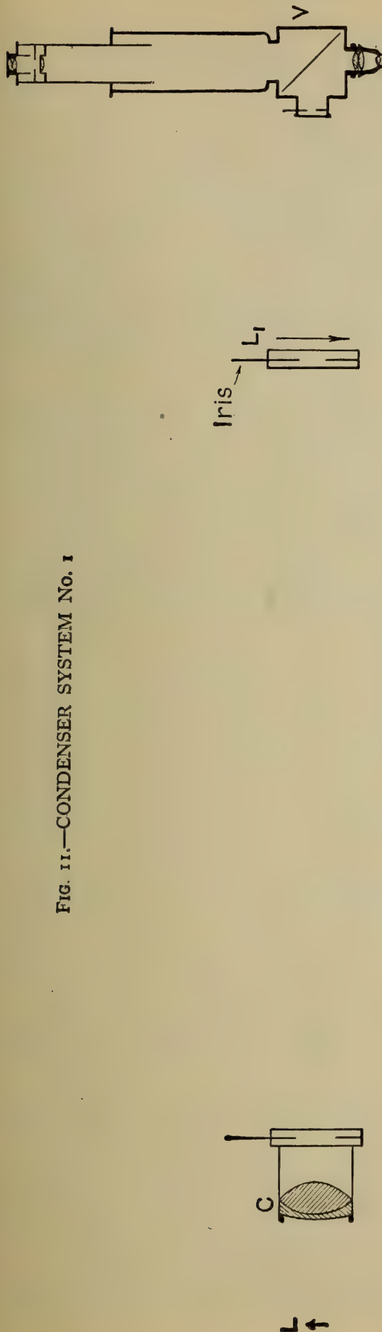


FIG. 11.—CONDENSER SYSTEM No. 1

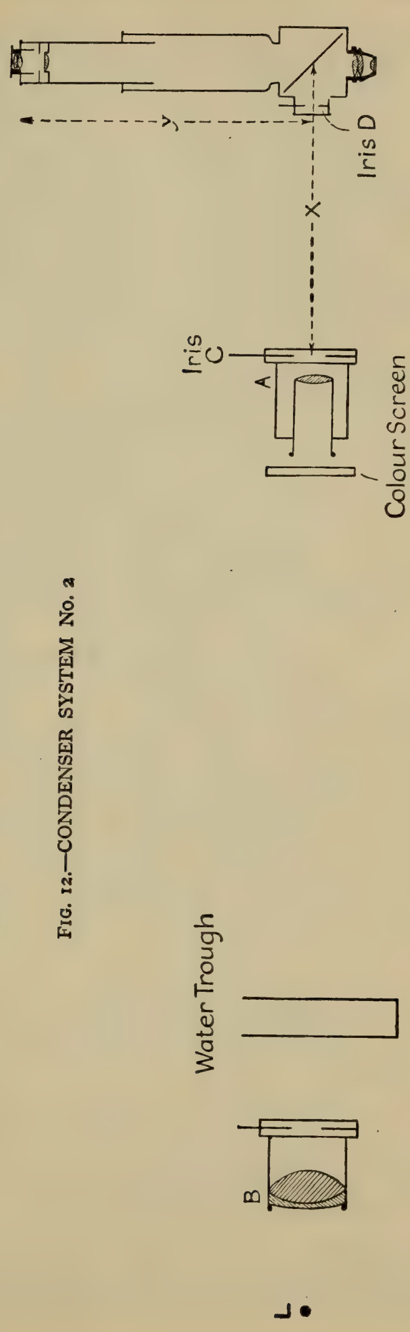


FIG. 12.—CONDENSER SYSTEM No. 2

1. Condenser B should be of short focus, about $2\frac{1}{2}$ in. to $2\frac{3}{4}$ in., and it should be well corrected. If the focal length is much less than $2\frac{1}{2}$ in. there will be difficulty in focusing owing to the size of the bulb of the Pointolite, should this lamp be employed. The lens used by the author is the Watson Conrady condenser, an achromatized aplanat. The enlarged image of the illuminant formed by B on A should have an even disc of light about 1 in. diameter.

2. Condenser A need only be about 1 in. or so in diameter. An iris diaphragm should be mounted on it as shown (C). This diaphragm should be closed until only slightly more than the field required is illuminated. By this means much stray light, likely to cause fog, is cut off.

3. The beam of light from condenser A must be large enough to fill the back lens of any objective in use. If the beam does not fill the back lens, the effect is equivalent to cutting down the aperture of the objective, with all the bad effects produced thereby. If an attempt is made to use one condenser only (placed at A) it will be found that, unless this has a very short focal length and the illuminant has a large area, the beam of light will not fill the objective.

The focal length of condenser A will obviously depend on the tube-length of the microscope. The author generally uses a 10-in. tube, and his lenses are adjusted to work with this tube-length. He has not found any difficulty in working with a short tube, however; the condenser A is simply moved 2 or 3 in. nearer the microscope, and condenser B adjusted accordingly. The fact that A is somewhat out of focus has not produced any noticeable effect.

The operations required in arranging the condensing system shown in fig. 12 should be carried out as follows:

1. Place the microscope in position on the base-board and put on the stage a previously levelled section.

2. Light up the illuminant L and adjust it so that it is opposite the opening in the illuminator (i.e. the same height above the base-board).

3. Open iris D and focus the section with a low-power objective. Only a small area in the field of view will be illuminated. Adjust the position of the lamp (or rotate the illuminator bodily) until this illuminated area is in the centre of the field. Now remove the eye-piece and, looking down the tube, gradually close iris D. The image of the latter will be seen in the back lens of the objective, and, as the iris is closed, the image should close concentrically with

the back lens. If it does not, adjust by moving the iris (if the latter is adjustable), or rotating the glass disc, or both. If any movement of the glass disc has been necessary, replace the eye-piece and re-centre the lamp L as described above.

4. Place condenser A in position so that distances x and y are approximately equal. Close iris C and centre the condenser by means of this iris so that the image of the latter seen in the field of view is central. The field should now be evenly illuminated, but the definition will not be good, as only a small part of the aperture of the objective is being used, as may be seen on removing the eye-piece and looking down the tube.

5. Place condenser B in position so that it focuses the illuminant on condenser A. Centre by moving B; do not move L. Condenser A will now be found to be projecting an even beam of light which completely covers iris D on the illuminator.

6. Close iris C until its image is just visible in the field.

7. On removing the eye-piece, the back lens of the objective should appear full of light; there will also be some flare visible, reflected from the mount and nosepiece. Close iris D until only about five-sixths of the back lens is illuminated. This cuts off all the flare and also prevents the lens being flooded.

If all the above operations have been carefully carried out, the microscope image will be evenly illuminated.

Occasionally the disc in the Pointolite shows small areas brighter than the rest. If these show in the microscope, the fault may be remedied by moving condenser B slightly nearer the lamp so as to throw the image on A somewhat out of focus. As a matter of fact, this image may be considerably out of focus without any bad result being produced in the microscopic image; there will, however, be some loss of light.

It is always advisable to use a low-power objective when centring the condensing system. Should a higher-power objective be required, it can be substituted afterwards. Any slight adjustment required can then be made with the centring screws on condenser A.

It may be mentioned that the photographs in figs. 2, A, 2, B, 3, C, and 3, D, were taken using the condensing system shown in fig. 11, while the remaining photographs in fig. 3 and those in figs. 4 and 5 were illuminated by the method shown in fig. 12.

The diagrams given in figs. 11 and 12 represent the author's apparatus, in which the microscope and camera are vertical, and the

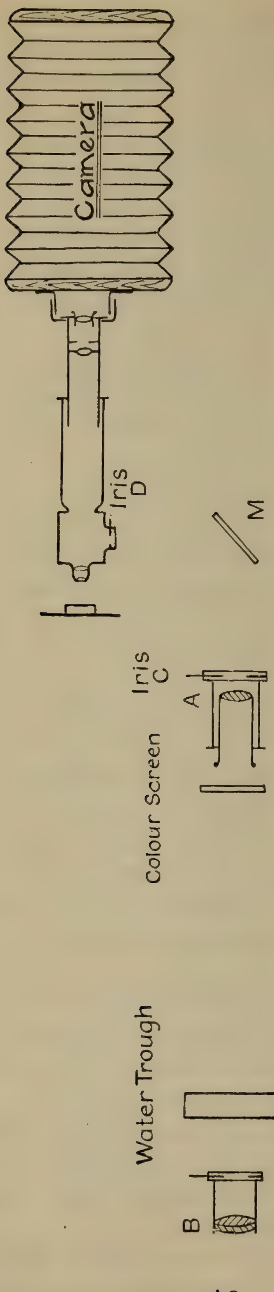


Fig. 13.—Condenser System No 2.—Alternative Arrangement for Horizontal Cameras

condensing system is perforce arranged at right angles to the axis of the microscope. If the camera and microscope are used in the horizontal position, obviously the condensing system may also be arranged at right angles to the microscope and camera, in which case the above description of the condensing system and the method of adjusting it apply equally well, the diagram being regarded as a plan instead of an elevation. Where, for any reason, the horizontal type of apparatus is used, this method of arranging the condensing system is, in the author's opinion, the best. Alternatively, however, the condensing system may be placed parallel to the axis of the microscope and to one side, as shown in fig. 13, the beam of light being reflected into the vertical illuminator by a mirror M. While this arrangement proves satisfactory for the method of illumination described above (the adjustment of the mirror M being the only addition to the procedure already given), it is not so suitable for the type of illumination required for low-power worker.[1] Care should be taken that the stand of condenser A does not foul the foot of the microscope, particularly when the latter is of the tripod type.

Instead of having the mirror to one side as shown in fig. 13, it may be mounted above the optical axis of the microscope, on a fitting carried by the tube. Such a fitting, using, however, a right-angled prism instead

[1] See p. 307.

of a mirror, is shown in fig. 14. Probably the chief merit of this design is that it causes the least alteration in the form of photomicroscope used for work with transparent sections, the only difference being the provision of extra lengths of adjustment on the stands for the various condensers and the illuminant. If, however, the microscope is of large size, very great difficulty may be experienced in getting condenser A (fig. 12) sufficiently near the 45° mirror (or prism). As in the case of the form with the side mirror, last described, an apparatus of this description is not suitable for low-power work, in which, as will be seen later, the condenser must be close up to the microscope.

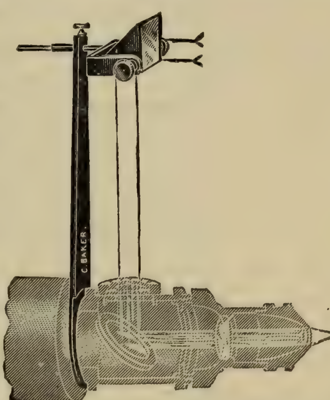


Fig. 14.—Totally Reflecting Prism for "Overhead" Arrangement of Optical Bench, for Horizontal Cameras.

Adjustment of Iris D.—The iris on the vertical illuminator acts precisely in the same manner as that on a substage condenser, and regulates the diameter of the cone of light focused on the section by the objective. If this iris be opened fully and then gradually closed while the section is observed with a medium or high-power lens, such as a 4-mm., it will be seen that the image, which is at first very flat and full of flare, improves and brightens considerably up to a certain point. Further closing, beyond this point, results in no further improvement in the quality of the image (except for a slight increase in the diameter of the sharp area), while the image becomes distinctly darker. Almost immediately, however, beyond this point the quality of the image gets worse owing to diffraction effects, which become very pronounced when the iris is reduced to a very small diameter. With most apochromats and semi-apochromats it will be found that the best results are obtained when the cone of light, as seen in the back lens of the objective, is about five-sixths of the diameter of the lens. With low-power lenses the same effects are produced, but the iris can be closed to a greater extent before any noticeable deterioration of the image is observed. Frequently, with such lenses, the increase in diameter of the sharp field, obtained by suitable stopping down, may be useful. Stopping down has also the effect of emphasizing any surface irregularities such as scratches or relief effects; where

the latter have to be shown, stopping down will prove helpful.

The author's general practice is to use the largest aperture the objective will stand, which as stated before is generally about five-sixths full.

Colour Screens.[1]—Only rarely is there any case in metallurgical work where a section demands special colour treatment. This simplifies the choice of screens very much and enables the metallographist to choose the screens most suitable for the objective.

For achromats and semi-apochromats the best screen is a green or yellow-green one used in combination with an orthochromatic plate. The author uses the Wratten tricolour green screen. A suitable plate is the Wratten Allochrome, or the Imperial Special Rapid Ortho, or other similar plate sensitive to yellow-green light. There is no advantage at all in using a panchromatic plate as the red sensitiveness of the latter is not required, rather the reverse. The field must, of course, be focused with the screen in position.

With apochromats, light of any colour may be used, but it is generally advisable to use blue light (especially with the higher powers) in preference to yellow-green or red, as the resolving power is thereby increased. It is always advisable, however, even with the best apochromats, to focus with the same colour of light as is used for photographing. The author's general practice is to focus with the blue screen in position (generally the Wratten tricolour blue), and then remove the screen and expose on a non-colour-sensitive plate. In this way the exposure is decreased considerably, since all blue screens have rather high exposure factors. This method is perfectly satisfactory even at the highest magnifications.

In the rare cases in which colour difficulties in a section are found, they fall generally under two headings:

(*a*) To show detail in a coloured part of the section. In this case, use a screen passing light of this colour with, of course, a plate sensitive to that colour. The author has never met with a case of this description in metallurgical work.

(*b*) To show contrast between constituents which are of about the same brightness but of different colours. For this purpose use a screen which passes light corresponding to one of the colours, and stops light of the other colour. As an example of this, the author had a mild-steel section in which the pearlite, being very coarse, appeared under low power to have a pale greenish-blue colour

[1] See p. 203.

after etching lightly. For various reasons it was not desirable to etch deeply (which would have darkened the pearlite considerably). A low-power photograph taken with either yellow-green or blue light gave practically no contrast between the ferrite and pearlite, but a perfectly satisfactory negative was obtained by using red light and a panchromatic plate.

Magnification.—It is very desirable that a comparatively small number of standard magnifications should be adopted for general purposes. The adoption of such a series allows comparisons between different photographs to be made much more easily. A series which fills most purposes in metallurgical work (excluding low powers, which will be dealt with later) is as follows:

$$\left.\begin{array}{l}\times\ 50\\ \times\ 100\end{array}\right\}\text{24 or 16 mm. objective.}$$

$$\left.\begin{array}{l}\times\ 250 \text{ or } \times\ 300\\ \times\ 500\end{array}\right\}\text{12 or 8 mm. objective.}$$

$$\left.\begin{array}{l}\times\ 500\\ \times\ 750\\ \times\ 1000\end{array}\right\}\text{4 mm. objective.}$$

$$\left.\begin{array}{l}\times\ 1000\\ \times\ 1500\end{array}\right\}\text{2 mm. objective.}$$

For a great many metals a magnification of 100 diameters gives a very good idea of the grain size of the material and is therefore a most useful figure.

There is no advantage in using a magnification above about 1500 diameters except under special circumstances. All the detail which a modern apochromat of the highest numerical aperture available is capable of showing can be seen at 1000 to 1500 diameters. Any further increase in the magnification is in the nature of an enlargement of the detail already shown, and can be obtained equally as well by enlarging a negative taken at 1000 to 1500 diameters as by photographing direct at the higher magnification. For example, all the detail shown in figs. 2, A and 2, B could be seen quite well at 1000 to 1500 diameters; this detail, however, was almost too fine to reproduce well by any photomechanical process. This case, therefore, is one of " special circumstances " referred to above when an enlargement to 3000 diameters or so is an advantage.

Although the principle of standard magnification should be adhered to whenever possible, it should not be insisted on too

rigorously. The best magnification to use for any section is the one which shows the required feature in the best possible manner. Broadly speaking, the lowest magnification which will show the structure is the best, as by so doing a larger field is obtained and hence greater possibilities of showing variations in the structure. When photomicrographs are intended to be reproduced by photomechanical processes, the limitations of the latter should be kept in mind and a sufficient magnification employed, as mentioned above, to allow the finest detail in the photograph to be reproducible.

It is an easy matter to calculate the magnification given by any combination of objective, ocular, tube-length, and camera, if the focal length of the objective and magnifying power of the ocular are known. Using a tube-length of 250 mm. and the $\times 6$ projection eye-piece, the magnification obtained on the plate is given by:

$$\frac{A \times 6}{B},$$

where A is the length of camera in millimetres, and
B, the focal length of objective in millimetres.

The camera-length is measured from the shoulder of the eye-piece (where it rests on the tube) to the ground glass of the camera. If the tube-length is altered from 250 the above fraction is multiplied by $\frac{TL}{250}$, where TL is the actual tube-length employed. With the $\times 3$ eye-piece the magnification is, of course, half that given above. With Zeiss apochromats and many semi-apochromats and achromats the calculated figures are quite accurate. Some achromats, however, are not accurately marked, and there may be a considerable error in the calculated magnification. The calculated figures may be checked by using a stage micrometer graduated in $\frac{1}{10}$ths and $\frac{1}{100}$ths of a millimetre, and measuring the distance apart of the lines in the projected image. Most stage micrometers are ruled on glass, however, and it will be found exceedingly difficult to see or focus the lines with higher-power objectives used with vertical illumination. Micrometers ruled on a strip of polished metal are much better; such micrometers used to be made by Zeiss and possibly other makers.

Focusing.—Having arranged the section under the microscope and adjusted the illuminant and condensing system, using the microscope visually in the ordinary way, the projection eye-piece is adjusted for the required camera extension, light-tight connection

made with the camera, and the latter extended to the requisite distance. Light-tight connection is easily made by means of a couple of brass flanges fitting as shown in fig. 15.

Using the ground-glass focusing screen, the section is adjusted, if necessary, so as to bring the required field into the centre. After having placed the necessary colour screen in position, final focusing is done with a plain-glass screen and a focusing glass. The latter should be of low power (only magnifying very slightly), and when resting on the outer surface of the focusing screen should focus accurately the inner side of the latter. This can easily be adjusted by focusing on a piece of printed paper held against the inner side of the screen.

When a long-extension camera is used some means have to be provided for working the fine adjustment of the microscope from the screen end of the camera. The author must confess he has not seen a perfectly satisfactory arrangement, but the best method is to have a light rod running the length of the camera and supported on brackets screwed to the base-board, with a milled head at the focusing end and at the other a small grooved pulley which is connected with the milled head of the fine adjustment. There is no doubt, however, that it is preferable, whenever possible, to do without any such method of extended focusing, and herein lies a further decided advantage of the vertical form of camera. In this form of apparatus, with any extension of the camera up to about 24 in., it is quite easy to reach the focusing screw with the hand while observing the image on the screen, and as it is doubtful whether any greater extension is really necessary it would seem that for such cameras there is no need for any such extended focusing arrangement. As a matter of fact, the author scrapped the one fitted to his apparatus years ago; he found it was not necessary, as he could reach and operate the fine adjustment head at any extension of the camera he required.

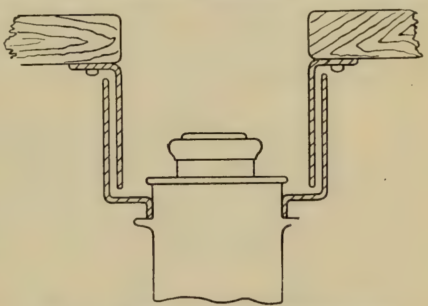


Fig. 15.—Light-tight Flanges for connecting Microscope and Camera

Exposure.[1]—The type of plate used, as noted earlier, is

[1] See p. 175, for physical chemistry of exposure.

governed by the kind of lens, and suitable kinds have been already suggested for achromats and semi-apochromats. For apochromats one can either use a good brand of special rapid plate, or, if the illuminant is very brilliant, so that the exposure with these is rather short, a slower plate such as an ordinary or a process plate may be used. The latter type of plate especially is useful for subjects possessing very little contrast, as such plates give contrast very easily. They also have generally a finer grain than the more rapid varieties, often of considerable value if an enlargement has to be made from the negative. It should be remembered that, broadly speaking, apochromats tend to give flatter images than achromats, owing to the greater amount of flare found in the former lenses, as mentioned on page 291. For such lenses a plate giving contrast easily is very helpful. With regard to exposure, only general information can be given, the required amount varying with so many conditions. As some guide, however, the following may be useful:

Section: typical ferrite and pearlite (mild steel).
Illuminant: 500 c.p. Pointolite.
Condensing system: as described (fig. 12)
Disc illuminator: iris adjusted to five-sixths full.

Objective.	Mag.	Plate.	Screen.	Exposure.
24 mm. apo. N.A. 0·30	100	Wratten process	None	3 to 5 sec.
24 mm. apo. N.A. 0·30	100	Wratten allochrome	Wratten tri-colour green	20 to 30 sec.
4 mm. apo. N.A. 0·95	500	Wratten process	None	10 to 20 sec.
2 mm. apo. N.A. 1·4	1000	Wratten process	None	20 to 40 sec.

With any given objective the exposure at different magnifications (other things being equal) varies as the square of the magnification. With different objectives, but using the same eye-piece, tube-length, and camera-extension, the exposure varies inversely as the square of the diameter of the opening in iris D (when using the condensing system shown in fig. 12). The exposure is, of course, affected considerably by the brightness of the section, particularly at high powers, when one often wishes to show the detail in the darkest parts of the section.

It is worth while for the beginner to use deliberately a dozen

or so plates in trying the effects of varying exposure and development.

Development.—Any standard developer may be used. As a general rule, however, photomicrographic negatives require longer development than, for example, landscape negatives, in order to get sufficient contrast. On this account the time of development with some of the ordinarily used developers may be rather long. For this reason the author, for some time past, has used a rather strong hydroquinone developer which gives contrast very rapidly. This is made up as follows:

A.	Hydroquinone	25 gm.
	Pot. metabisulphite ..	25 ,,
	Pot. bromide	25 ,,
	Water to	1000 cc.
B.	Caustic soda (pure).. ..	50 gm.
	Water to	1000 cc.

Use equal parts of A and B.

With this developer ample contrast can be obtained in two to three minutes. It also gives very good density.

Whatever developer is used, the most satisfactory method of development is by time. As in other branches of photography it is very much better to stick to one developer and find out its capabilities. Three or four plates used to find the time of development giving the best amount of contrast are well spent.

Printing.—This is done in precisely the same manner as in other branches of photography. Probably the best effects are produced by the black-and-white image given by bromide or gaslight paper, while a glossy surface paper is admirably adapted for showing fine detail.

Oblique Illumination.—The vertical illuminator gives what is known as vertical or direct illumination. The light falls vertically on the section, and hence a plane surface at right angles to the optical axis reflects the light back into the lens and therefore appears bright. An irregular surface, on the other hand, scatters the light to a greater or less extent, and hence appears dark. If, however, light is directed on to the section at an angle to the optical axis of the microscope, a plane horizontal surface reflects the light outside the microscope and appears dark, while some of the facets of an irregular surface would probably be at the right angle to reflect the obliquely directed light into the microscope, and would, therefore, appear to be light. Speak-

ing generally, therefore, the effects produced by direct and oblique light occupy the positions of positive and negative to each other.

Oblique lighting is not of very great use metallurgically. When required it is best obtained by a parabolic reflector, which either fits on to the objective or on to the stand. Obviously it can only be used with low-power lenses (24 or 16 mm. is about the highest power that can be used). When using such a reflector as that shown in fig. 16, an approximately parallel beam of light is projected on to it. The light is reflected downwards and strikes the section obliquely. The small 45° mirror which is shown in fig. 16 is intended to give vertical illumination; it is swung aside as shown by the dotted lines when oblique light is required.

Vibration.—In all industrial laboratories, and in many others, a great deal of trouble is experienced owing to the effects of vibration. For this reason it is highly desirable that the exposures required, especially at high powers, be as short as possible. Even when the exposures are comparatively short (e.g. a few seconds) they still give plenty of time, in the case of the higher powers, for vibration to have considerable effect. Where the camera, microscope, and illuminating system are all mounted on one base-board, as the author recommends they should be, much of the effect of vibration can be eliminated by swinging the whole apparatus on springs. The author's instrument, so mounted, is shown in Plate X (p. 533). The base-board is carried by two steel plates to which are attached four $\frac{3}{8}$-in. steel rods. The latter are hung from four small spiral springs which are in turn attached to a wooden framework supported on a rigid foundation as shown in the photograph. The strength of the springs should be suitably chosen so that they support the apparatus freely. It may be mentioned that, with this suspension system, photographs at 1000 and 1500 diameters were successfully taken although the laboratory was within 50 yards of four 8-ton steam-hammers and also adjoined three sets of railway lines running into the works. Where the vibration is not excessive, swinging the apparatus on cords in a similar manner will probably be adequate. Any such suspension method is much more effective than placing the apparatus on blocks of rubber or layers of felt.

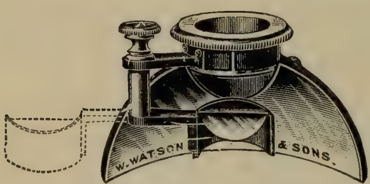


Fig. 16.—Parabolic Reflector for Oblique Illumination

Low-power Photomicrography

It is frequently desirable to be able to reproduce, at low magnifications, fairly large areas under vertical illumination. With ordinary low-power objectives (e.g. 50 mm. and 75 mm.) it is possible to take photographs at, say, 20 to 40 diameters, using the condensing system shown in fig. 12, but in general the field is only small, about 2 or 3 mm. diameter. If attempts are made to get a larger field, trouble is at once experienced with the illumination and often the definition falling off at the edges. Frequently a very large field is required if the photograph is to serve its purpose, as, for example, with groups of flaws, very coarse structures, and segregated areas. Often such subjects require a field 10 to 15 mm. diameter and a magnification of only 10 or 15 diameters.

For such purposes the author devised the system of illumination

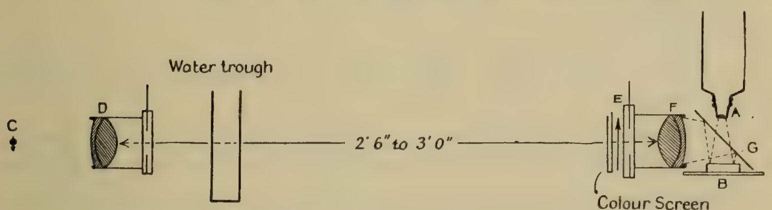


Fig. 18 —Condenser System for Low-power Photomicrography

shown in fig. 18. A is the objective, and for most purposes the author uses the 35-mm. projection lens made by Zeiss, though probably equally good results could be obtained with some of the small photographic lenses of similar focal length made by various opticians. The condenser D forms a considerably enlarged image of the illuminant C (500 c.p. Pointolite) at E, close up to the second condenser F, and the latter in turn focuses the image (after reflection at the 45° cover-glass reflector G and the surface of the specimen B) on the lens A as indicated roughly by the dotted lines. Both D and F are Watson Conrady condensers, and it is possible to illuminate evenly a section about 1 in. diameter. The cover-glass G, $1\frac{7}{8}$ in. $\times$ $1\frac{1}{4}$ in., is mounted in a light brass frame which fits on to the objective. The frame is pivoted for adjusting the illumination. Fig. 19 (Plate XI, p. 535) shows the microscope and condenser F set up. It will be noticed that F is quite close to the stage.

The 35-mm. projection lens is used without any eye-piece, and in order to obtain as large a field as possible the draw-tubes

of the microscope are removed. The outer tube is lined temporarily with a piece of black cloth to prevent reflections. For such work it is essential that the outer tube of the microscope be as large as possible. The instrument used by the author is the Works Model made by Watson's, London, and this has an outer tube 2 in. diameter and $4\frac{3}{4}$ in. long, enabling one to use practically the entire field of the 35-mm. lens. Fig. 20 (Plate XII, p. 537), which shows a sample of burnt steel, is an example of a low-power photograph, magnified 10 diameters, taken by this method.

The range of magnification with such a lens depends on the minimum and maximum lengths of the camera. The author's apparatus allows a range of 9 to 23 diameters with the 35-mm. lens.

The camera-length (l) required for any magnification (m) is given by the formula

$$l = (m + 1)f,$$

where f is the focal length of the lens; l is, of course, measured from the lens itself to the ground glass.

In low-power work the actual magnification used must depend to a large extent on the size of the field to be reproduced. In a photograph of a flaw, for example, it is frequently of more importance to include the whole of the flaw in the photograph than to take the latter at some definite magnification, such as 10, 15, or 20 diameters.

For photographs at 30 to 50 diameters one may use a similar method of illumination with an ordinary 50-mm. objective. In this case, as the field is smaller, condenser F (fig. 18) is moved a little farther from the microscope so that it focuses condenser D on the specimen. The lamp C being focused on F by D, this produces an even disc of light, about 6 mm. diameter, on the specimen. Condenser F thus acts precisely as a substage condenser, and its iris diaphragm is regulated in the same way as D in fig. 12. Fig. 21 (Plate XII, p. 537), taken at 40 diameters with a 2-in. objective, shows the results obtainable by this method. It illustrates the banded structure produced in Muntz metal by hot working. For definition and size of field it may be compared with fig. 5, B, which was taken with the same lens, but using a vertical illuminator and the condensing system shown in fig. 12.

For still lower powers one may use a short-focus photographic lens (2 to 6 in. focus). In this case the microscope is removed

altogether and the lens mounted on a small tube, with a spiral or rackwork focusing movement, fitting on to the front of the camera. To obtain vertical illumination in such cases the condensing system shown in fig. 22 may be used. B is the Watson Conrady condenser, which throws a parallel or slightly divergent beam of light on the ground glass A. The light from this is reflected on to the section by the 45° reflector C (a thin lantern-slide cover or an old quarter-plate negative which has been cleaned up). The idea is to produce an evenly illuminated disc of light on the ground glass, the light from this being reflected down on to the section by the 45° reflector. Such low magnifications are especially valuable for steel sections etched with one of the "copper" reagents (such as Stead's, Rosen-

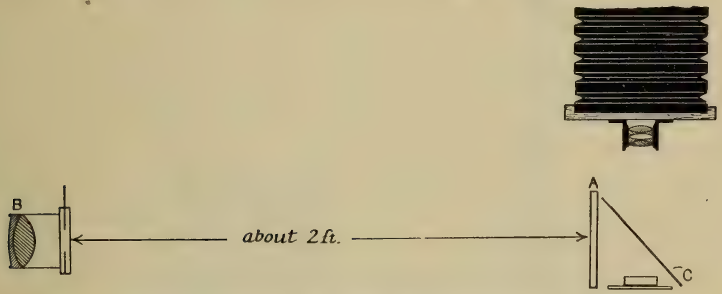


Fig. 22.—Vertical Illumination for Lowest Powers (up to about ×5)

hain's, or Le Chatelier's). As an example, fig. 23 (Plate XIII, p. 539) may be shown representing the crystals in a small steel ingot. If oblique light is required for such powers, a very convenient method is to use a couple of 100-c.p. half-watt lamps mounted on stands and placed on opposite sides of the section.

Reproduction of Small Samples

It is frequently necessary to be able to photograph a small sample, such as a section, a fracture, or a small tool, to show the extent and location of some particular feature. To some extent these can be dealt with by using the apparatus last described, but when such reproductions are about the same size as the original or less, it is more convenient to use an ordinary camera of quarter-plate or half-plate size, of the double-extension type. The camera is best mounted on a block which slides in grooves along a substantial base-board, at one end of which a small easel (with vertical

adjustment) is fixed, as shown in fig. 24. With a lens of 5 or 6 in. focus the base-board should be 3 to 4 ft. long. Diagrams or small thin sections can be pinned on to the easel, and the sliding block, on which the camera is mounted, enables one to adjust the camera easily so as to obtain the image the required size. Larger sections can be accommodated on small blocks in front of the easel. The best illumination in these cases is undoubtedly daylight; when this is not available a half-watt lamp (about 100 or 200 c.p.) placed on either side, can be used. If the article is not flat and it is essential to show the relief effect, the lighting should be from one side only.

If polished sections have to be reproduced, the lighting cannot be from the side or the bright surface will appear to be dark. Such samples can often be reproduced quite satisfactorily by standing them on a large piece of smooth white paper (extending some distance in front of the section) and slightly tilting them towards the camera. By this means the paper reflects light almost vertically on to the sections and the latter appear quite bright. Fig. 25 (Plate XIII, p. 539) illustrates this; the samples shown had been polished and locally corroded, and it was desired to show the pits as dark marks on a light background. The photograph was obtained in the manner described.

It is well known that large sections of metals etched to show the macrostructure often look very brilliant when in the etching fluid, but lose a lot of their brilliancy when they are dried. Such samples are best photographed while wet, the section being immersed in a dish of water, spirits, or light oil; if this is not convenient, much of the brilliancy may be restored by covering the section with a thin film of glycerine or light oil.

Immersing the section in the dish of fluid necessitates the camera being vertically above the specimen. Such an arrangement as that shown in fig. 26 can be made quite easily from a heavy block of wood for a base-board, and steel tubes and tube fittings for the camera support. This arrangement of the camera is often very useful when photographing small forgings or machine parts of complex shape. The latter are then simply laid on a light background, thus obviating much of the trouble of supporting such complex shapes. Brightly polished curved shapes are always difficult to photograph on account of reflections from various parts of the surfaces. If the object is to show a small flaw in such an article, a better effect can often be obtained by lightly etching the surface so as to dull the brightness.

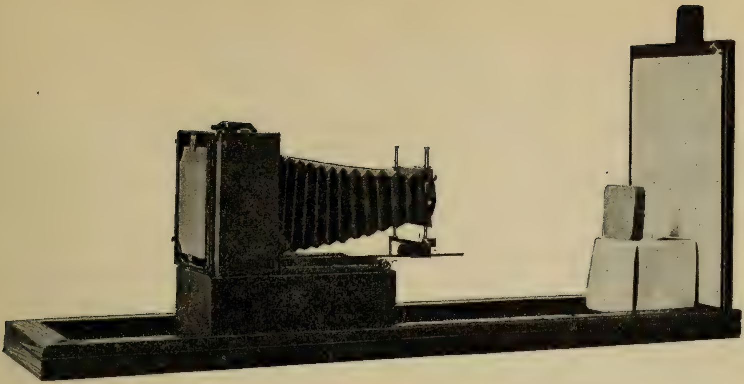


Fig. 24.—Camera, Base-board, and Easel for photographing Small Objects

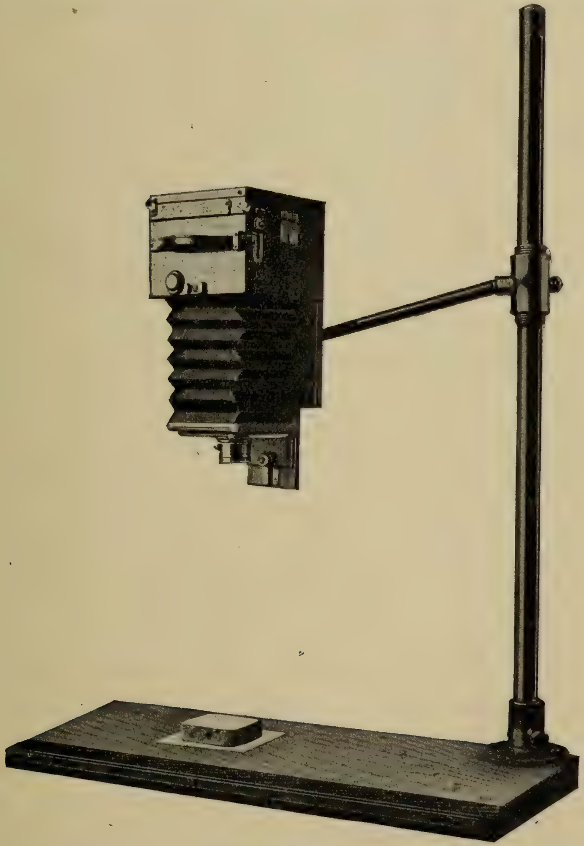


Fig. 26.—Base-board and Stand for Vertical Arrangement of Camera

Facing p. 310

The Photography of Machinery and Plant

The practice of photographing machinery or plant during or after erection either to show the progress of work, the importance of special details, or the appearance of the whole after completion, is one which has become very wide-spread. Work of this description is of a very varied character, and the demands on the apparatus frequently very severe.

A well-built stand camera is essential, and this should be fitted with rising and cross fronts and swing back. As regards size, much depends on what is required; as a general rule the author prefers to use a small camera (quarter-plate or 5 in. by 4 in.), and to enlarge if necessary. A half-plate camera is often used, and for many purposes gives a print which is large enough; the negatives can of course be enlarged in the same way as the smaller ones, but the enlarging apparatus is more costly. The lenses used should be good ones; there is no doubt at all that the high-priced anastigmat pays for itself. For general work the lens should not have too short a focal length (about 5 in. for quarter-plate), but often a wide-angle lens (say $3\frac{1}{2}$ in. to 4 in. on a quarter-plate) is an absolute necessity owing to confined situations. Plates should always be backed, and for most purposes those of a fast type are required. For overcoming the tendency to halation [1] which is present even in backed plates, the special portrait film made by Kodak has been recommended.

The lighting will often be found a matter of great difficulty when machinery has to be photographed in the shop. Where the shop has a large doorway and the machine can be moved, a good plan is to place it just inside the doorway at an angle of about 20° (so as to get a side lighting, which shows the contour of the parts better than front lighting), and then set the camera straight opposite it. Most machine shop floors are black or nearly so and do not reflect much light; much can be done, however, by laying newspapers on the floor all round the machine. Wherever possible a light background should be used; such a one can be made by fastening old sheeting (or similar material) on framework, or one can use sheets of newspaper gummed together and similarly mounted. Even when the background has subsequently to be blocked out it is better to have a light background when taking the photograph, as it is then much easier to do the blocking out, particularly round the darker parts of the machine.

[1] See p. 35, 36

When the machine cannot be moved, great difficulty may be encountered, especially when the shop is rather dark. Often there is a considerable amount of vibration, and since the exposure may be rather long it frequently happens that it is only possible to take the photograph when the shop is standing. If artificial light has to be used, magnesium ribbon may be employed, but great care is necessary to diffuse the light well. The ribbon may be burnt in a box behind the camera on one side, the open end of the box being covered with tissue paper or other translucent material. Further smaller pieces may be burnt behind the camera, keeping them moving all the time, so as to lighten the darker shadows.

Brightly polished parts of machinery often cause trouble owing to reflections. Daubing such parts with a thin paste of vaseline and whiting will often obviate this.

It is generally advisable, if possible, to have the machine "posed" by someone who knows the particular part or idea to be emphasized. Any moving parts should be fixed in that part of their travel which shows their object most distinctly. Such posing often makes a considerable difference to the success or otherwise of the photograph.

In the photography of plant, for example to show the progress of erection, the conditions are extremely varied. They often call for the use of the various movements of the camera mentioned earlier, and of lenses of widely varying foci. It is impossible to give any general directions. Each case has to be attacked on its own peculiarities. There is wide scope for judgment in the use of focal length of lens, plate, and filter.

A novel method of detecting changes in buildings, complicated groups of objects, or anything subject to slight change, was recently described by Stillman.[1] A negative is made of the group of objects in which change is expected. After the change is supposed to have occurred, a second negative is made with the same camera on a plate of the same kind and from as nearly as possible the same position as used in making the first negative. A positive is printed from one of the negatives, and is superimposed upon the other negative so as to bring them into register, and the combination is viewed against a source of light. When the photographs are properly made, those parts of the combination which correspond to the unchanged portion of the group of objects will appear as a field of practically uniform density, while a change in the group

[1] *Bureau of Standards*, Scientific Paper 392.

will be revealed by a considerable departure from this uniform appearance. It is suggested that progress in engineering work (e.g. construction of bridges) could be shown by this method, also any changes in complicated documents and drawings. The original memoir should be consulted for details.

THE APPLICATION OF PHOTOGRAPHY TO RECORDING INSTRUMENTS

The use of the " optical lever " for measuring the deflection of moving parts of instruments is too well known to require any explanation of the principle underlying its action. It has had numerous applications in metallurgical and engineering work. The Roberts-Austen recording pyrometer and the Saladin double galvanometer are well known metallurgically, while the oscillograph is of great value to electrical engineers.

One of the most recent applications of the principle is in the Dalby optical load-extension recorder, which was designed by Professor W. E. Dalby to obtain load-extension diagrams of different materials with great precision, and with elimination of the inertia effects of the beam and jockey weight which are found in an ordinary tensile testing machine. A description of this apparatus will serve to indicate the methods used in such a recording instrument. The principle of the apparatus is shown diagrammatically in fig. 27. Light from a lamp A passes through a small hole in a diaphragm E, and is then reflected by a fixed mirror B on to a concave mirror C, from whence it is reflected to the mirror D, and thence to the photographic plate P. E and P occupy the positions of conjugate foci with respect to the concave mirror C, and hence a sharp image of the brightly lit hole in E is formed on P. The load on the specimen under test is measured by the elastic extension of another bar termed the " weigh-bar ". The pull of the tensile machine is transmitted through couplings X and Y to S, the specimen under test, and W, the hollow weigh-bar, which are coupled together by the muff coupling Z. The cross-sectional areas of W and S are so arranged that the load required to break S only stresses W within its elastic limit. Consequently the stress acting on S at any instant is proportional to the extension of W at that time. This extension is measured by the mirror C which rests on three points, one of which is supported by a light rod F. The bottom end of the latter is

pointed and rests in the conical hole in the weigh-bar as shown in the diagram. The extension of the weigh-bar causes the mirror C to rotate on an axis parallel to the plane of the paper. Hence any such movement causes the beam of light, after reflection at D, to move on the photographic plate P in a plane at right angles to the surface of the paper. The extension of the test piece S during

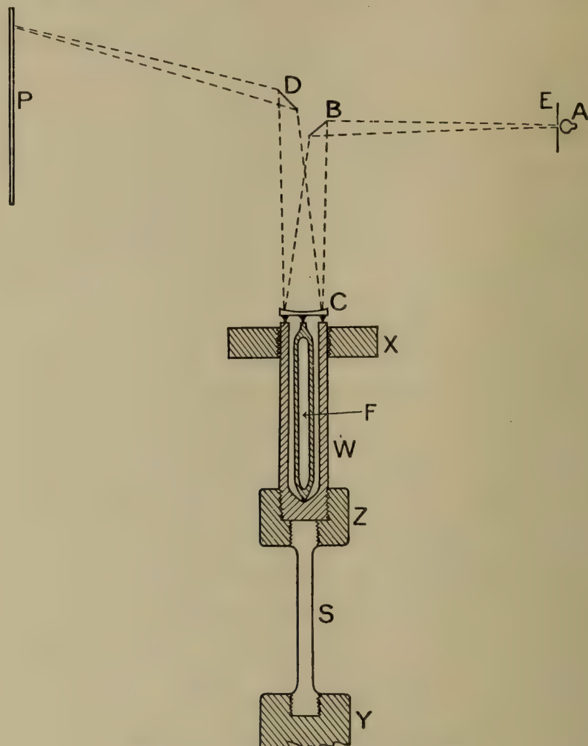


Fig. 27.—Diagram of Dalby Extensometer

the test produces, by means of a suitable linkage, a rotation of mirror D on an axis perpendicular to the axis of rotation of mirror C. This rotation of mirror D causes the beam of light to move along the plate P in a plane parallel to the surface of the paper, and therefore perpendicular to the movement produced by the rotation of mirror C. Hence during the progress of the test a curve is traced out, the ordinates of which are the load on the test piece and the corresponding extension of the latter. Since the measurement of the load does not depend on the movement of a heavy jockey

weight along a beam, but on the purely elastic extension of a bar, it is free from inertia effects, and the curves obtained represent accurately the relation of load to extension during the progress of the test. Such an apparatus, for example, enables the time effect on tensile tests to be determined even at high speeds of testing; thus Professor Dalby has published curves obtained from mild-steel test pieces pulled in four seconds. The curves obtained also bring out in a very marked manner the fall in stress which occurs, when testing mild steel, immediately the yield point is passed.

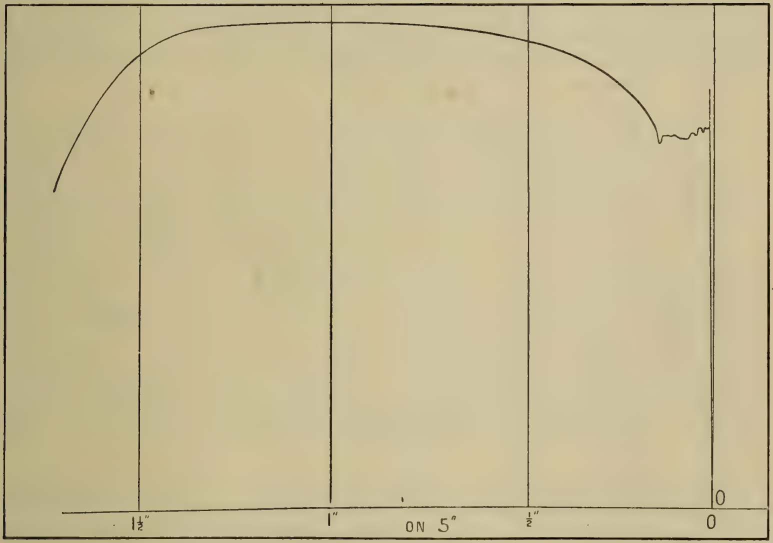


Fig. 28.—Stress-strain Diagram of Mild Steel obtained by Professor Dalby

The apparatus has recently been put on the market by Messrs. Buckton & Co., of Leeds, and is made in two patterns, one of which allows a total extension on the test piece of 1½ in. to be recorded, and therefore serves for the reproduction of the complete stress-strain diagram. In the other form, the extension is magnified to a much greater extent in order to show the position of the limit of proportionality. The type of diagram obtained with the first instrument on a sample of mild steel is shown in fig. 28.

It is obvious that similar methods may be used in any case where the simultaneous variation of two different quantities has to be measured, providing the variation of the respective quantities can be made to operate a couple of mirrors. Where it is a question

of measuring a variable against time, the measurement of the latter can be made either by rotating one of the mirrors by clockwork or by doing away with the second mirror and moving the photographic plate by clockwork. In the latter case, the plate may be replaced by a sheet of photographic paper wrapped round a drum which is rotated by the clockwork. This latter method is employed in the Roberts-Austen recording pyrometer.

Sometimes it is impossible to arrange that the axes of rotation of the two mirrors shall be perpendicular to each other. The best-known example of this is the Saladin double galvanometer, where the simultaneous deflections of two galvanometers have to be recorded, both axes of rotation of the mirrors being of course vertical.

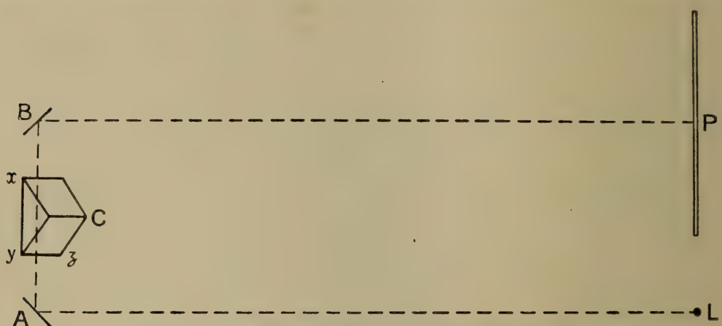


Fig. 29.—Diagram of Saladin Double Galvanometer

In this case the horizontal deflections of the beam of light after reflection at the first mirror are turned into vertical deflections by passing through a right-angle prism, which is placed with its base parallel to a line joining the two mirrors, but inclined at an angle of 45° to the horizontal, as shown diagrammatically in fig. 29. In this A and B represent the two mirrors, C the prism, L the light, and P the photographic plate. The edge *xy* of the prism is horizontal and parallel to the line joining the two mirrors. The edge *yz* is inclined at an angle of 45° to the horizontal. Mirror A is concave, and L and P occupy the positions of conjugate foci with respect to it. Mirror B is plane, and is made sufficiently long vertically to take care of the vertical movement of the beam of light due to the horizontal deflections of mirror A. Obviously the two mirrors should be as close together as possible.

The methods briefly described here can clearly be applied to other types of apparatus.

CHAPTER VIII

Photomicrography

Introduction

The recording by photography of the appearances presented by objects subjected to the magnification that they receive when viewed on the stage of a microscope dates from quite an early period in the practice of photography.

The first note of a photographic record of a microscopic object of which we have knowledge dates from the year 1837, when the Rev. J. B. Reade employed a sheet of leather sensitized with a solution of nitrate of silver. Later on he replaced the leather by sheets of paper tanned with an infusion of galls and sensitized with nitrate of silver. Upon these prepared sheets he was able to project by means of his microscope a magnified image of a flea. With an exposure of five minutes he obtained an image of his object. This he subsequently fixed with hyposulphite of soda. He was thus able to obtain a record which saved the time and expense that a hand drawing demanded.

In 1853 a paper by J. Delves describes the employment of a photographic process for the securing of representations of the minute structure of objects which are only rendered visible by the application of the microscope. This communication "On the Application of Photography to the Representation of Microscopic Objects" is to be found in the *Transactions* of the Royal Microscopical Society of London.

The ease of the manipulation of the modern dry plate has undoubtedly led to an ever-increasing employment of the photographic process when faithful recording of detail in structure is required. With the present-day capabilities of such plates, their rapidity in action, and, owing to their improved colour sensitiveness, their ability to record visual appearances—truthfully not only as regards

surface markings, but also in the matter of securing correct tonal values, or even a representation in natural colour—it is certain that the use of photography will become more and more employed in the branch of research that we are considering.

The knowledge that we at the present time possess with regard to the character and speed of the photographic plate we are employing, and the methods of its development, together with the inclusion in our armentarium of screens or filters which allow of the use of light of restricted and varying wave-length, play a great part in the securing of modern results.

These purely photographic advances have been aided by the improved optical apparatus, with the highly corrected lenses and condensing systems now available. In this direction progress has been made in that the modern microscopical lens has a "resolving power" which was not available in years gone by. As an example, the present-day apochromat may be quoted.

In the writer's opinion perhaps the most powerful factor in the recent improvement of photomicrographic technique was the formation in London in 1911 of the Photomicrographic Society. This society, in which the microscopist meets the photographic worker, has been the means of a very marked advance in the recording by photography of the appearance of microscopical specimens. The society is rapidly becoming a large one, and exercises an important influence in its sphere.

The employment of the photographic plate for recording purposes is steadily replacing the use of the drawing pencil in conjunction with the camera lucida, though there are occasions when, owing to the artistic licence allowed to the draughtsman, the latter is to be preferred. Varying planes of view can be embodied in a pencil drawing that are outside the possibilities of a single focus of a micro-objective, and at the same time the artist is able to exclude non-essential detail which would complicate a record provided for teaching purposes. It should be remembered, however, that draughtsmen of such skill as Tuffen West, who provided the excellent results embodied in the plates accompanying the *Micrographic Dictionary* (Griffith and Henfrey), are not often available. Drawings can never be so scientifically correct as a properly executed photomicrograph made by an experienced worker with knowledge of the best apparatus to employ, and the requisite acquaintance with the various photographic processes which will be made use of in the production of the finished positive print.

The space at disposal in which to deal with a subject having so many outlying features is inadequate to allow of anything approaching an exhaustive description of the processes, but an attempt will be made by the writer to bring to notice most of the salient points, a knowledge of which is required by those engaged in the production of photomicrographs. For more complete information the reader has in *Practical Photomicrography*, by J. E. Barnard, and in the *Handbook of Photomicrography*, by Hind and Randles, two up-to-date books from which much valuable information can be obtained. They are both well illustrated and contain much that is of service to those engaged upon the work with which they deal.

The field now embraced by photomicrography is one with a very wide area, covering as it does the work of histologists, bacteriologists, and pathologists to which has been added more recently the recording of results obtained by the microscopical examination of rock structures and metals. For the latter, microscopes of different design, fitted with special illuminating devices so as to secure the appearance presented by an etched and polished metal, are now available.

Section I.—Low-power Photomicrography

Low-power Photomicrography without the Employment of a Microscope may be effected by the use of a long-extension camera fitted with a photographic lens of short focus. Quite a large amount of work can be satisfactorily done with a triple-extension half-plate camera the dark slide of which is provided with a quarter-plate carrier. I would strongly advise the employment of quarter-plates ($4\frac{1}{4}$ in. × $3\frac{1}{4}$ in.). Their smaller cost and their suitability for making lantern slides ($3\frac{1}{4}$ in. × $3\frac{1}{4}$ in.) by contact are sufficient reasons for their use. The author has designed an effective repeating back for insertion at the back of his half-plate camera, by which he is able to make two exposures of an object upon a quarter-plate. This very useful addition carries a quarter-plate single metal dark slide, and allows of two records being obtained on the same plate, one with, say, double the exposure of the other, or one taken using a colour filter and the other with an unscreened light. On development there may be a very marked advantage in one or other of the images. Provided that the shift of the plate has been properly made, and this is secured by the insertion of a stop in the repeating frame, two negatives ($3\frac{1}{4}$ in. × $2\frac{1}{8}$ in.) are obtainable, and

are of such size as to be quite suitable for the making of a lantern slide. For experimental exposures the use of this device has obvious advantages. A Cooke anastigmatic lens, series V, 4·1-in. focus working at an aperture of $f/8$, fitted on the front panel of a half-plate camera at an extension of 20 in., will secure a magnification of 4 diameters. If employing a still shorter focus lens of 3 in. with the same camera-length, the magnification will be increased to 6 diameters, whilst with a 2-in. lens used under similar conditions an enlargement amounting to about 9 diameters will be obtainable.

A series of lenses fitted with the R.M.S. thread for microscopes, designed on the lines of photographic anastigmats, is now available, and is largely used for low-power photomicrography, either with or without the employment of the microscope. They have an advantage in flatness of field, covering-power, and depth of focus over ordinary microscopic objectives, and are fitted with an iris diaphragm which can be closed down to secure greater depth—a point of importance in the obtaining of photographs of objects having various planes. The greater penetration gained by working a lens at small aperture is a matter of common knowledge to the ordinary photographer. The usual microscopic objective sacrifices depth of focus in favour of resolution. For the securing of records of thick subjects, especially when illuminated by direct and not by transmitted light, these lenses, styled microplanars and micro-summars, may be used with considerable advantage. Their speed depends, of course, upon the aperture at which they are working. They are made of 1-in., 2-in., and 3-in. focal length, and they will in some cases cover an object whose diameter approaches that of their focal length. Up till recently they have only been produced abroad, but there is now available an excellent series of similar anastigmatic lenses computed on similar lines and manufactured in Birmingham by Messrs. Aldis Brothers. They have on the market a 2-in. and also a 3-in., both of which are capable of excellent work, and can be used either on the microscope or fitted to the front panel of a camera. They will be found to secure the critical definition that is associated with Aldis photographic lenses. I prefer the 3-in. lens as being more generally useful. It will be found to cover an object about ¾ in. in diameter, and works well at an aperture of $f/6·5$. Quite recently the same firm has introduced two series of photomicrographic lenses, one working at $f/3$, and the other at $f/4·5$. Both are provided with iris diaphragms.

For this class of photomicrography the camera may be used either

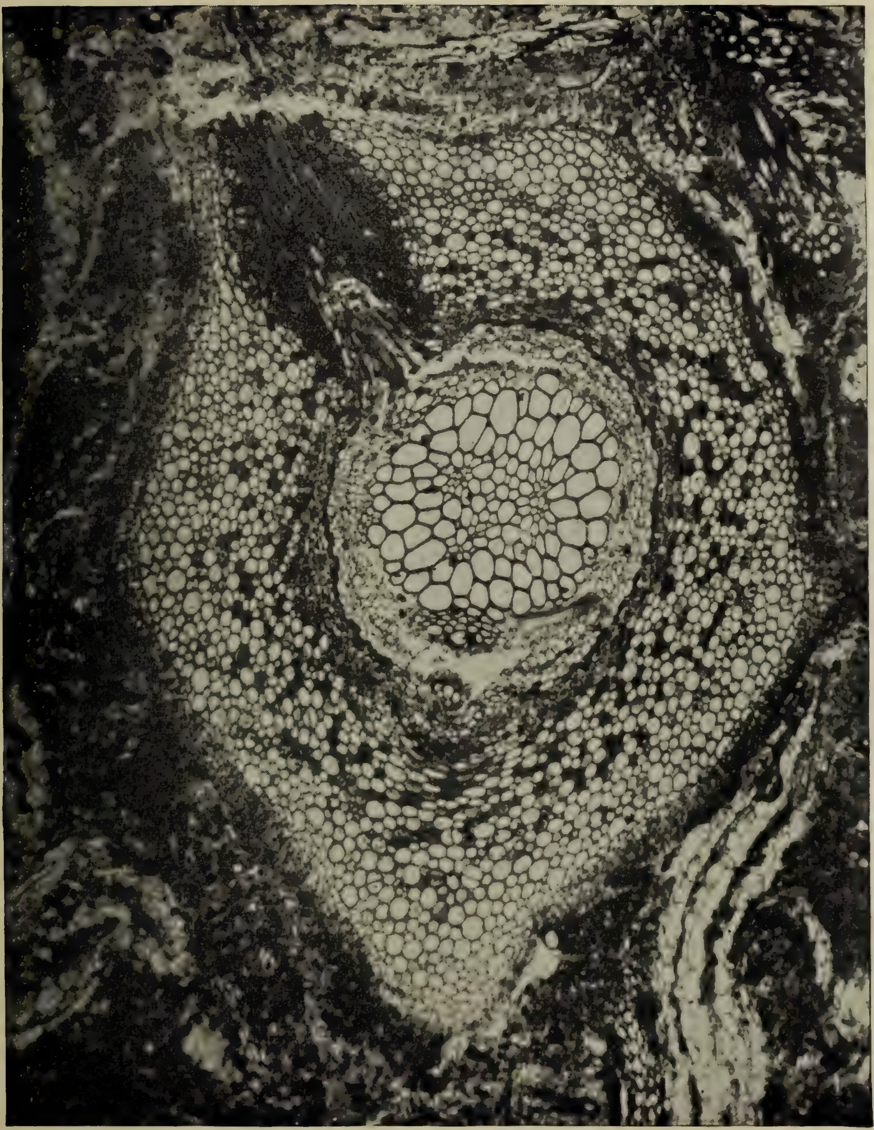


Fig. A.—Coal Plant Fossil, ×33 (section through the petiole of a fern, *Botryopteris cylindrica*)

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in the horizontal or the vertical position. If the former be employed the camera should be screwed or clamped to a base-board to give it rigidity, and space should be provided on the base-board for the arrangement of the illuminant, the condensing lens, and the apparatus for holding the object to be photographed. Artificial light will generally be used under these conditions.

The vertical position is more convenient for some purposes, as, for example, an object photographed in fluid. Various forms of support for a camera used in this position are obtainable, but it requires but little skill in carpentry to devise a base for the camera to be used in the upright position. A sheet of plate-glass supported below the camera serves as an excellent rest for the object photographed. Cards of various tints or a piece of black velvet placed a few inches under the glass shelf will provide satisfactory backgrounds.

Illumination by daylight or even sunlight may be employed when photographing in this position, which is also suitable for any form of artificial lighting that may be desired. A concentration of light is obtained by the use of a bull's-eye condenser. Working under the conditions we have been considering a powerful source of artificial light is not required—a kerosene lamp or an inverted incandescent gas-burner will satisfy all purposes.

When working with the horizontal camera the object may be one to be illuminated by transmitted light, in which case a bull's-eye plano-convex lens, or even a condenser from an optical lantern, is placed between the object to be photographed and the source of light. The condenser should be placed behind the object supported in a holder (the clamping vice used in the binding up of lantern slides serves the purpose well) at such a height as to be on a level with the centre of the camera lens. Centre the lamp so as to secure an evenly illuminated area on the ground glass of the camera. The position of the condenser has also to be carefully attended to so as to obtain perfect alignment in the entire optical system, for upon this depends the success of the exposure. The object to be photographed can now be moved too and fro until it occupies the position required on the ground glass and appears to be fairly sharp. Critical focus is then obtained by racking out or in the back of the camera. A good focusing glass should be employed for the final focus.

It may be of advantage to subdue the intensity of the light, or to get rid of any pattern of the meshes of the incandescent mantle evident on the object by the introduction of a sheet of finely ground

glass in the course of the beam of light, preferably as near the light source as possible. This will, of course, add to the length of the exposure necessary, as the light intensity is diminished considerably.

Exposure of the plate is made by drawing the dark slide, and then, when any vibration is finished, uncapping the lens, or if no cap be used, by removing a sheet of black cardboard so placed as to cover the lens. This simple procedure is less likely to be attended by harmful vibration than if an elaborate shutter is employed. The card can be easily replaced after the necessary exposure has been given, prior to the closing of the dark slide.

In employing *direct or incident illumination* the light source is placed alongside the camera in such a position that no direct light can reach the lens. A convex condenser is used for focusing the light upon the object supported in the holder, which will occupy a similar position in relation to the photographic lens that it did when using transmitted light. Focusing and exposure of the plate are effected in the same way as suggested in the previous example. The exposure necessary under these conditions will be considerably more than when working with transmitted light, which may be considered as ten times more powerful. In some instances it may be advisable to make use of a reflector on the side of the opaque object, remote from the direction from which the light employed is coming. This will tend to even up the illumination and to diminish the shadow in the final result, but usually the photograph is better taken without such procedure.

A source of trouble to workers in opaque objects is light reflected from the surface of the usual black paper upon which the object is mounted. Even the smoothest paper shows much disturbing grain when subjected to magnification. A way to avoid this granularity is to temporarily mount the opaque object upon a clear-glass slip, and then to place this slip upon a second slip blackened by the application of a black egg-shell enamel applied to its under surface. This will serve as a background showing practically no grain. A slip of red non-actinic photographic glass may be used in place of the blackened glass slip, and owing to its non-photographic character will afford a nice black ground for the finished photograph. Similarly, if a clean white background be considered more suitable a slip of white opal glass may be used to back up the clear glass slip upon which the object is mounted, and will be found to be far more satisfactory than white paper or card, both of which will show marked grain under the microscope. Attention to details

such as these will have a very decided effect in the appearance of the final print.

Indications for length of exposure will be considered later when dealing with work in which the microscope is used. Seeing that the lenses so far recommended to be used approximate to ordinary photographic lenses, the amount of exposure may be calculated on similar lines to those adopted in ordinary photography by artificial light. The luminosity of the ground-glass focusing screen, in the hands of those accustomed to this work, serves as a fairly safe indicator as to the amount of exposure required.

A new accessory has been recently introduced in the shape of the *Swift-Wheeler photomicrographic attachment*, which consists of a microscope tube capable of being fixed to the front panel of a photographic camera, replacing the photographic lens. For low-power work it will provide all the apparatus required for elementary photomicrography, and with it objects may be recorded with magnifications up to about 150 diameters.

Section II.—High-power Photomicrography

Photomicrography employing a Microscope.—Successful work in this direction calls for the use of a microscope having several features in its construction and fittings that deserve attention.

The *stand* should be a solid one, well balanced so as to be perfectly steady when inclined into the horizontal position. The type of *foot* found in the English model, taking the form of a tripod or claw, is to be preferred to the horseshoe foot, a feature of the Continental type of instrument. The coarse and fine *adjustments* of the tube should be well made and free from wobbling or backlash, for a great deal depends upon the proper working of the adjustment in securing perfect focus, and a microscope wanting in this direction cannot fail to be a source of continual annoyance to its owner. The *microscope tube* should be of the short type of $6\frac{1}{2}$ in. length, and provided with a telescopic inner draw-tube supplied with a rack-and-pinion movement, and a millimetre scale indicating the total length of the tube when in use. The diameter of the tube should be preferably of large size (up to 2 in.) rather than that usually made, which is about $1\frac{1}{4}$ in. This point, however, is not an essential, though when working without an eye-piece the larger tube will allow of the projection of a larger disc than that obtainable with a tube of smaller calibre. The inner surface of the tube should

be dead black so as not to cast reflections causing a troublesome flare spot. Some workers recommend the lining of the inner tube with velvet or black cloth. The *stage* should be a large one. It is a convenience though not essential to have one with rotating movement. Whether to employ a mechanical stage or not is a matter to be decided by the individual worker. The writer regards this in the light of a luxury, and more often than not when engaged in photographing an object removes his mechanical stage and substitutes a pair of spring clips. With practice any movement of the object required can be secured by the fingers, which in time become very efficient. The circular hole in the stage should be of large size. The *substage* for carrying the substage condenser and its accessory fittings is a part of the instrument which demands attention, for upon these depend the proper illumination of the object. The *condenser* should be capable of approach or the reverse to the under surface of the object. This should be obtained by a rack-and-pinion movement. Provision should be made for the swinging-out of the whole substage, and also for the proper centring of the condensing system. To secure perfect illumination this latter action is a *sine qua non*. An iris diaphragm and a fitting for holding glass filters and the wheel stops used in dark-ground illumination is provided in all the best substage fittings. The *substage condenser* should be of moderately high power, with a front lens removable so that when using the back combination only, i.e. when employing low-power objectives, it will act as an efficient low-power illuminator. An Abbé condenser is one of the cheaper forms, and will be found to be quite efficient, though some may prefer one of the much more expensive and more highly corrected kinds. The *mirror* should be removable, with one side plane and the other concave. Parallel rays are projected by the former surface, and convergent ones by the latter. The mirror is not, however, much used in photomicrography at the present time.

The *objectives*. The choice of these must depend upon the class of work to be undertaken. For the purposes of the bacteriologist *apochromatic lenses*, both dry and oil-immersion, will be required, and with these lenses, very highly corrected as regard spherical and chromatic aberration, a highly magnifying eye-piece can be used without " breaking down " the resulting image. The increased numerical aperture securing greater illumination free from colour defect, and the increased comfort for visual work are all features in which an apochromatic surpasses an achromatic lens.

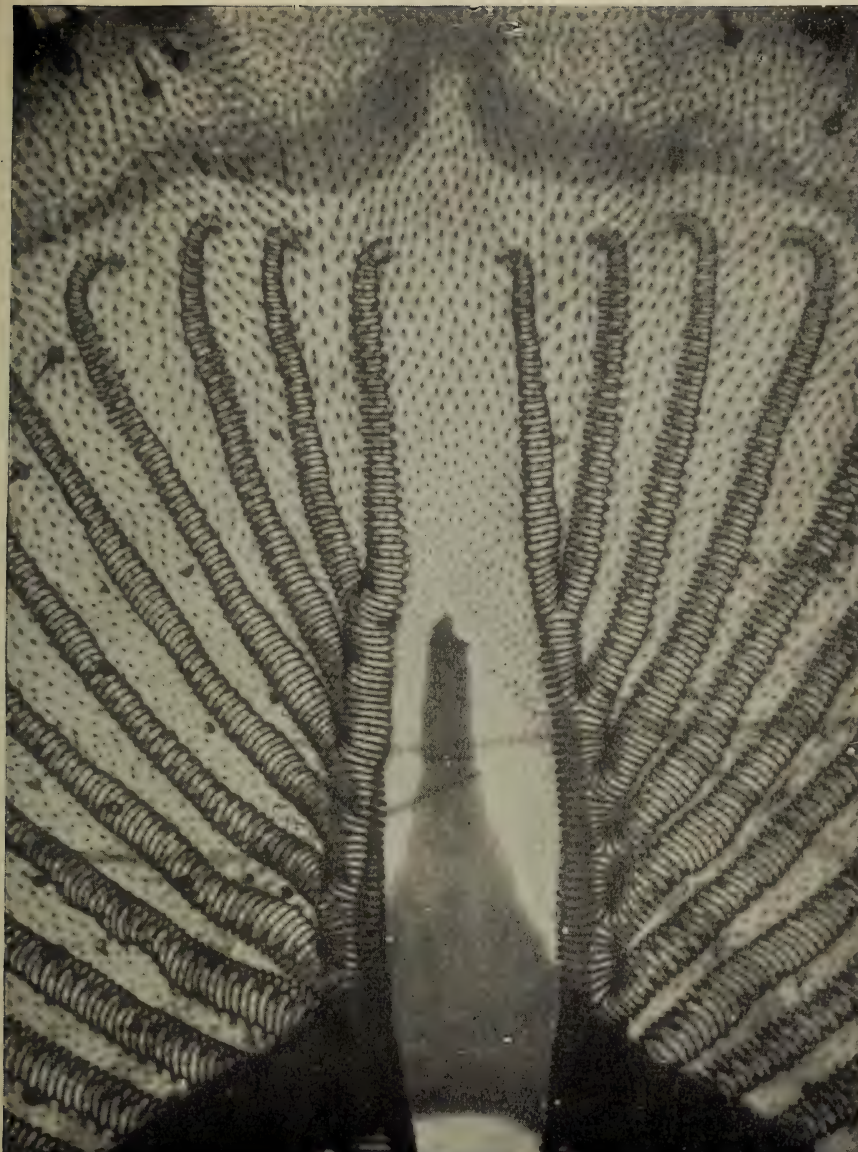

Fig. B.—Tongue of Blow-fly, × 300

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A cheaper form of objective known as *semi apochromatic*, *fluorite*, or *holoscopic* is now available. They are capable of excellent high-power work, and, being constructed of fluorite, excel in correction over the ordinary achromatic objective, and though only corrected for two colours, and thus inferior to the apochromats, their results closely approach those obtained by the more perfectly corrected lenses.

Achromatic objectives of modern construction are so corrected chromatically that two colours come to the same focus. They are also corrected for spherical aberration. These lenses are primarily intended for visual work, but will provide excellent photomicrographs, especially when employing monochromatic light or using one of the green filters, under which conditions the work obtained by an achromatic lens of good construction will not fall far short of that secured by one of the more highly corrected and consequently much more expensive apochromatic lenses. The field of an achromat is often much flatter than that provided by the apochromat. Apochromatic lenses must always be used in conjunction with a compensating eye-piece.

For the production of good photomicrographic results it is wise for the beginner not to attempt work requiring the highest magnification. He should be content to accustom himself to work with low-power objectives, and then gradually to proceed to exposures on much higher magnifications.

A battery of good achromatic lenses of such focus as 3 in., $1\frac{1}{2}$ in. $\frac{1}{3}$ in., and $\frac{1}{6}$ in., the last possibly a fluorite lens, will enable the worker to produce results in the attaining of which he will acquire unconsciously considerable experience which will serve him when he comes to employ lenses of much shorter focus and of increased correction in more advanced work. Given two objectives of the same focal length but with different numerical apertures, the one with the greater numerical aperture will have better resolving power, or in other words, will more perfectly show and differentiate spots or lines when closely lying together. Later on a $\frac{1}{12}$-in. oil-immersion objective may be added to those previously noted.

Eye-pieces or oculars, of which there are several varieties to be obtained, may or may not be used in combination with an objective for securing a photographic representation of a microscopic object. Some workers favour the employment of an eye-piece whilst other prefer not to use one. In the first instance the magnification secured

by an exposure when employing an eye-piece is greater than that obtained without one, but this can be compensated for by the substitution of shorter-focus objectives or increased camera-extension. It is the writer's practice almost always to use an eye-piece, except in a few cases of very low magnification where the extra enlargement obtained by the eye-piece is not desired. The eye-pieces usually employed with achromatic objectives are of the form known as *Huyghenian.* They consist of a combination of two plano-convex lenses and are made with various magnifying powers designated by numerals or letters. In practice it will be found advisable not to employ an ocular of a power higher than necessary. The higher the power used the greater the loss of light, and at the same time any error or defect in the working quality of the objective is proportionately increased with the magnification of the eye-piece.

With apochromatic objectives a special form of compensating ocular must be employed. The *compensation or correction eye-piece* provides for the improvement or neutralization of the under-correction in apochromatic objectives. This defect renders the employment of an ocular of compensating character necessary when working with this type of objective, which should never be used without one. A third form of eye-piece specially designed for photomicrography is that known as a *projection eye-piece.* They are only made to give small magnifications, and are intended for projection and not for visual observation. Two powers are obtainable, $\times 2$ and $\times 4$. The latter is generally recommended as being the more useful. They may be employed with either apochromatic or achromatic lenses. They have only quite a small field and carry a rotating collar for focusing the diaphragm that they contain. Exceedingly crisp definition may be secured by the employment of this projection type of eye-piece, though at the same time practically everything required can be done without the inclusion of this form of eye-piece amongst the optical apparatus. It may be remarked that an apochromatic objective will bear, without loss of crispness in the image, the employment of a compensating eye-piece of a very much higher magnification than that employable with an achromatic objective. The higher-power achromats from $\frac{1}{6}$ in. upwards with a large numerical aperture, owing to their being frequently under-corrected, will be found to provide better photomicrographic results if in place of the Huyghenian eye-piece a compensating or projection one is employed.

A feature in the modern *holoscopic eye-pieces* by Watson is that

they are so arranged that by adjusting the separation of their component lenses they may be used with either achromatic or apochromatic objectives at will. Of this last form of eye-piece and their capabilities of work the writer has but little knowledge.

The inclusion of the following oculars, ×12 compensating and ×4, ×6, ×8 Huyghenian, in an optical outfit should serve the purpose of most workers, and their employment with the set of

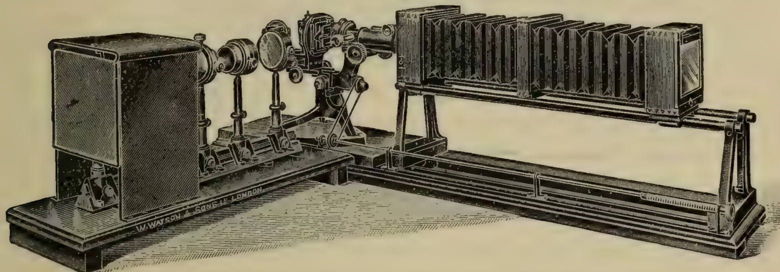

Fig. 1.—Watson's Laboratory Apparatus arranged for Metallurgy

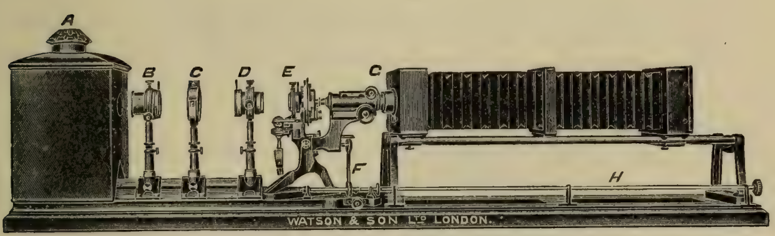

Fig. 2.—Watson's Laboratory Photomicrographic Apparatus

objectives previously suggested should enable the worker to obtain any magnification that he may desire.

Camera to be Employed.—As a rule a half-plate camera used for the exposing of quarter-plates as advised in an earlier section of this article will be found most satisfactory, though for work of special character a larger camera may be required. Various forms of camera specially designed for photomicrography are obtainable from opticians (figs. 1 and 2). The students' camera supplied by Watson & Sons is of sound and serviceable construction, and if a more elaborate installation is desired their laboratory form is available. By the same firm a heavier form capable of being used either as a horizontal or a vertical apparatus known as the Duplex is provided.

A similar apparatus designed for the same purpose by E. Leitz

is of a good working form (figs. 3 and 4). These are patterns by two only of the makers of such cameras—many other and probably equally good forms are obtainable.

If it be decided that a special camera be purchased, then one with a square bellows allowing of an extension of at least 36 in. should be selected. A *reversing back* carrying the focusing screen should be included, as this will be found to be of considerable convenience in working. The *focusing screen* is a feature that should be carefully considered. The usual camera form is of but little use when we come to focus critically minute structure. Some workers employ a clear plate-glass screen, using with this a focusing eye-piece so as to be able to view the aerial image. The author favours the employment of a finely chemically etched ground-glass screen provided with a number of clear-glass spaces where the image in the air may be viewed as in the case of the plate-glass screen. If these clear spaces be provided not only in the centre of the screen, but at various distal parts thereof, a highly effective focusing device is secured. A satisfactory view of the evenness of the illumination and a general view of the object are visible to the unaided eye as upon an ordinary ground-glass focusing screen, and in addition the aerial image may be critically focused with the help of a magnifying eye-piece over any of the clear spaces. Lines drawn on the half-plate ground glass indicate the size and position of a quarter-plate ($3\frac{1}{4}$ in. $\times$ $4\frac{1}{4}$ in.), a full lantern plate ($3\frac{1}{4}$ in. $=$ $3\frac{1}{4}$ in.), a $2\frac{5}{8}$-in. circle, and a $4\frac{1}{4}$-in. circle. These indications will be found of great use in composing the picture that is desired. Upon the front surface of the central clear space should be scratched a fine cross. This will correspond with the sensitive surface of the plate in the dark slide, and serve as a means of setting the focusing eye-piece correctly to suit the worker's vision, so that when this cross and the details of the aerial image are found to be equally sharp he may feel certain that the object has been satisfactorily focused. With high-power work in which the illumination is not very bright, without the employment of the aerial image, critical focus would not be obtainable with any degree of certainty. To photographers who have never focused an image in the air there is a surprise in store. They will be astonished at the extraordinary power that such an image places in their hands. An ordinary fine-grain focusing screen may be converted into a ground screen having clear spaces by the cementing, with Canada balsam, of a few clean circular micro covers to the ground surface of the glass. In this case a small cross may be drawn with a finely

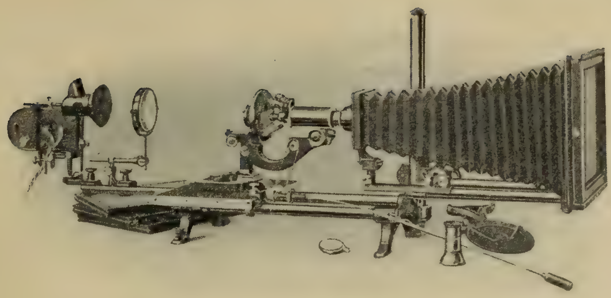

Fig. 3.—Leitz Apparatus used Horizontally

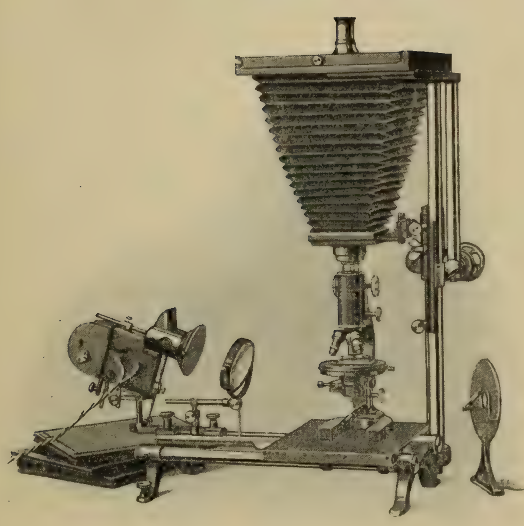

Fig. 4.—Leitz Apparatus used Vertically

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pointed hard lead pencil on the ground surface of the central spot prior to the application of the balsamed cover. The action of the Canada balsam is to fill up the interstices of the ground glass, and to render them quite transparent. When using an ordinary ground-glass screen it will be found that the application of a small quantity of vaseline to the ground surface will render the screen much finer and more translucent. A very effective focusing screen may be made by slightly exposing a photographic plate to light and then developing it with a non-staining developer till it becomes somewhat grey. After fixing with hypo and well washing, a very serviceable focusing screen will be obtained, and if the plate, whilst being exposed to light, using say a wax match at a distance of a few feet, is protected by superimposing a clear glass plate of similar size to which discs, &c., of black paper have been stuck in position corresponding to the sites required to be clear, a specially designed screen for our purpose can be easily manufactured. In addition a subsequent treatment of the plate with a solution of iodine, followed by the bathing in a very dilute solution of ammonia, will convert the silver into a practically grainless form and provide a screen more efficient in allowing fine focus to be obtained than the ordinary commercial article.

In cases where the microscope can be swung out of alignment with the camera on the working bench—and such a movement cannot be too strongly recommended, as allowing for an easy visual examination of the object—a white card screen may be hinged to the side of the back of the photomicrographic camera on the same plane as that occupied by the ground glass of the focusing back. Upon this card, placed in correct position in relation to the axis of the microscope, an image can be projected identical with that recorded upon the ground glass when the microscope is brought back in alignment with the camera. By this arrangement a very easy and certain means of obtaining even illumination can be secured, and by the use of an opaque white screen built on the lines suggested, one can get a projected image telling us whether the substage condenser is correctly centred, and whether the diaphragm of the projection eye-piece, supposing that such an eye-piece is being used, has been properly focused.

The *front of the camera* used for photomicrography should be provided with several interchangeable panels, each having a central circular opening. One should be fitted with a flange having the R.M.S. thread. This will take a low-power micro-objective, to be

used as described earlier without the employment of any microscope A second should carry a flange for use with a short-focus photographic lens, a third having a central opening somewhat larger than the rim of the microscope eye-piece. It is advisable that this opening should be in the dead centre of the camera, and of such a size as to receive easily the end of the eye-piece or the microscope tube when no ocular is employed. It should not fit the eye-piece tightly, but allow of its insertion without actual contact between the camera front and the microscope. This is a point of importance in providing against tremor and for securing ease in subsequent work. Further, it may be found of advantage to provide for a slight rise, fall, and lateral movement in the panel.

A light-tight connection between the camera and the microscope is important when making an exposure upon the photographic plate. To effect this a light-tight sleeve of black velvet may be employed, but a more workable device is secured by the providing of a stiffened cardboard ring, 1 in. in depth, fixed to the camera front and slightly larger than the opening in the panel for the eye-piece which it surrounds. On the microscope tube a similar circular fitting is provided, sliding on the tube, and at the same time bearing a collar somewhat larger than that mounted on the camera front panel. A satisfactory exclusion of any harmful light will be effected when the movable portion carried on the microscope tube is slid over the smaller fitting carried on the panel. The action is very much the same as that when the lid engages the body of an ordinary pill-box. Both tubes should be coated with a dead black so as to eliminate any possible chance of reflection. The employment of a light trap constructed on the lines as suggested above will eliminate the possibility of vibration, which might cause trouble when the microscope and camera are connected up if only by the application of a velvet sleeve.

As indicated in an earlier paragraph the camera may be used either in the horizontal or vertical position, and this holds good when employing the microscope in conjunction with the camera.

Various Forms of Photomicrographic Apparatus.—Some, of very costly character, are available for use in either of these positions, and in some cases the same apparatus allows of either form of manipulation. Examples of such are supplied in the illustrations by two out of many makers. The selection of the type of apparatus to be obtained must be determined to a great extent by the class of work contemplated. The writer designed and produced his own

outfit as far as base-board, &c., was concerned, and in his hands it has been found to work well. Others may prefer the article produced commercially and provided with all the niceties of the saddle-back or geometric slide optical bench. Work of good technique can be done without the employment of any such elaborate apparatus, which, however, will save time if work has to be produced under pressure.

For a *horizontal apparatus* a solid base-board of seasoned wood 4 ft. 6 in. long, 11 in. wide, and 1 in. thick should be provided. At one end of this should be secured by a central countersunk screw a smooth second board 3 ft. long, 16 in. wide, and $\frac{3}{4}$ in. thick, capable of rotating smoothly on the base-board. This top board will support the microscope placed horizontally, the illuminant, the condensing system, &c., and allow of the swinging out of the whole clear of the camera. This movement permits of the visual examination of the correctness of illumination and the selection of the particular part of the object desired for photography more easily than is possible when judging these points from the appearance of the projected image on the ground-glass screen. A stop provided at the angle of the base-board will secure that when the top table is rotated back, the optical apparatus is brought back to strict alignment with the camera, and that the position of the source of illumination remains undisturbed. For ease of setting up the apparatus, the microscope feet slide between battens screwed to the rotating top, and similar guides are used for maintaining a perfectly aligned system, including the source of light, the collecting lenses, the cooling trough, and any filters in use. It is an essential for satisfactory work that not only the axis of the microscope tube and the substage condenser but also the whole of the illuminating and collecting system should be in strict alignment with the camera, and that a straight line drawn through the centre of the whole should be absolutely at right angles with the centre of the ground glass of the camera.

At the end of the base-board, remote from the rotating top carrying the microscope, &c., the camera must be supported and clamped in such a position that it is secured in true alignment with the axis of the optical system of the microscope. The support of the camera should be so designed as to allow of the various extensions of the bellows working satisfactorily both forwards and backwards. The former movement will allow of the making of the light-tight connection previously referred to, and the latter movement carrying the

focusing screen may be employed to secure extreme accuracy of the image to be photographed.

A length of bellows extension exceeding about 20 in. will make it impossible to reach with the hand the fine adjustment of the microscope whilst the worker is engaged in viewing the object on the focusing screen. This renders necessary the use of a *long arm*, such as Hooke's handle, the well-known pattern for the purpose, or a rotating metal rod, one end of which carries a grooved wheel connected, by a resined silk cord, with the fine adjustment of the microscope, and the other end so placed on the base-board at the focusing end of the camera as to be easily rotated by the worker engaged in the act of focusing. Various devices in this connection are available. The points to be sought after are the sweetness of working, free from backlash or lateral displacement of the microscope. To provide against this a compensating counterpoise is embodied in one or two of the forms of focusing rod in use. The long arm must be unshipped when the microscope is rotated for visual examination, though this has been provided for by making the rod in two parts which are easily keyed together or separated, so that in revolving the upper board no disturbance of the fine adjustment gearing is necessitated.

A *scale* indicating in inches the extension of the camera at which the photograph is being taken should be embodied on the base-board, as this will be found to be of great use in not only determining the magnification employed, but in providing at a glance the details of extension for inclusion in the record kept of each individual exposure.

The success of the photograph depends to a great extent upon the apparatus employed being of such a character as to minimize or prevent vibration during the exposure. For this reason a microscope and camera embodying solidity and supported upon a base of stout proportions should be selected, and the table carrying the whole should be perfectly steady upon its legs. To absorb vibration it has been the writer's practice to stand the base-board upon two pads, one at either end of the board, of several layers of thick felt—possibly india-rubber sponge material would be even more efficient—and this has absorbed any shock and has worked very satisfactorily. Various methods designed to prevent tremor have been suggested. The working in a basement rather than on an upper floor, the provision of a concrete floor, the slinging of the whole apparatus from the ceiling, or the clamping of the base-board to a stone mantel-

shelf, are amongst them. With care, however, work can be carried out with certainty without these. Points in the method of exposure, and the adaptation of the microscope to the camera, have been previously referred to in this connection.

As suggested in an earlier paragraph the microscope and camera may be employed in a *vertical position*. To allow of this various types of apparatus are on the market. An illustration of one which can be used either horizontally or vertically will serve to indicate the method of its use (see figs. 3 and 4 on plate facing p. 328). A supporting device for the camera, holding it in such a position so as to engage the eyepiece of the microscope when the latter is standing vertically, may be made of wood, and will serve its purpose well. The same apparatus as that previously mentioned in connection with work not requiring a microscope may be used in conjunction with the microscope, in which case the easy removal of the plate-glass shelf must be provided for. When working by transmitted light with a vertical apparatus, the mirror of the microscope is employed for the purpose of illuminating the object just as it would be used in visually working with the microscope. In this detail the vertical operation differs from the horizontal when the illuminant is condensed by means of the collecting lens and no mirror is required.

Section III.—Illuminants

This brings us to the subject of illuminants. The form that this should take must depend upon whether the electric current or a coal-gas supply is available. In remote country districts neither of these is likely to be installed, and the photographer has to content himself with some other form of lighting.

Kerosene Lamp.—Light from the ordinary kerosene lamp is not to be despised, as satisfactory work can be done with it. It, however, lacks brilliance, so that its employment necessitates prolonged exposures which can be avoided by the use of a higher-power illuminant. A lamp of this type should have a flat wick. The paraffin should be of the best quality, and to it may be added a few blocks of camphor, which improves the luminosity of the flame. Even high-power work can be done with this form of light, employing the edge of the flame, which will give a more intense illumination than that obtained when the flat surface of the flame is used—a course usually adopted when working with low powers, where it

is difficult to obtain a uniform lighting of the field from the more restricted area of the flame edge.

Acetylene Gas, either used in a portable lamp such as the cyclist carries or produced in a generator, provides a more powerful and more actinic light than that from a kerosene lamp. The objectionable smell and the trouble of cleaning out the receptacle for the carbide after use, militate against the general employment of this form of lamp. Many workers using it produce highly creditable photomicrographs. The light value of a flame of acetylene is possibly some ten times greater than that available when using a paraffin lamp.

Oxyhydrogen Gas—employing cylinders of compressed oxygen and hydrogen in conjunction with a lime, or better a thorium, pastille, which is rendered highly incandescent by the gas passing through a blow-through or mixed jet—will provide a light of a much more powerful character and can be used for the highest-power photography. The necessary gases can be stored in cylinders under pressure, but where a house gas-supply is available, the hydrogen cylinder may be replaced by the employment of coal-gas from the main. Various forms of jet are procurable, and when worked with a Beard's regulator and a Pringle cut-off control, allowing for the easy securing of a proper admixture of the two gases, no real difficulty will be met with. A light of 500 c.p. is obtainable with a blow-through jet, and anything up to 2000 c.p. when a mixed jet is employed. Quite recently a little lamp has been designed for photomicrography by Mr. W. R. Biss, in which a small and restricted source of highly actinic light is secured by the use of a diminutive jet of coal-gas which is made to impinge upon a small pellet of thorium not larger than a pea. This becomes a source of highly incandescent light. In practice this form of illuminant has very much in its favour. By using it excellent photographic and visual work with the microscope can be done, and even in districts where there is no gas-supply this lamp may be used by employing a cylinder of compressed coal-gas.

Incandescent Gaslight.—Gas used with a mantle, preferably of the inverted form, is the illuminant employed by many workers. It is simple and convenient, though at the same time the heat thrown off and the tendency for the mesh of the mantle to show on the object to be photographed are points against it in use. The inclusion of a sheet of finely ground glass and an iris diaphragm in the path of the light rays will prevent the latter. This form of illuminant is

more particularly good in low-power work. The luminosity of about the same order as that from acetylene depends upon the newness of the mantle and the pressure and calorific standard of the gas supplied. Should these vary, the light will correspondingly be decreased or the reverse. In this an electric source of light has a very marked advantage.

With the electric current available, especially if of the continuous type, this means of illumination will undoubtedly be selected owing to its steady reliability and ease of working. It may be employed in various ways.

The **Nernst Lamp,** not at present procurable, provided a very satisfactory light for photomicrography, though the incandescent filament and heating coil were somewhat fragile and required delicate handling. The source of light was a small one of great brilliance, of constant power, and was in every way suitable for our purpose, though not of the capacity of an arc lamp. A Nernst lamp for use on 100-volt circuit with a single filament, provides a light approximately of ten times the actinic value of an oil lamp, but when run on a 240-volt circuit the intensity of the light as compared with that on the lower voltage is increased threefold. When owing to difficulties in obtaining Nernst filaments some form of electric lamp other than the arc and the mercury-vapour light was required, a highly efficient lamp was provided by the *silvering* of the outer surface of a *metallic-filament* lamp, say of 30 c.p., leaving only a small circular patch of about $\frac{3}{4}$ in. diameter unsilvered. This clear window is subsequently frosted, either with hydrofluoric acid or by coating it with matt varnish, and this, when the lamp is in action, becomes a circular disc of high luminosity obtained from reflections from all directions of the interior of the lamp. It provides a light of medium power of about the order of $\frac{1}{4}$-ampere Nernst running on 100-volt circuit. Good results can undoubtedly be obtained by the employment of this handy form of illumination. Since he first used this lamp the author has employed it almost exclusively, reserving the use of an arc for occasions when a much greater light-source was required. The lamp may be silvered by the depositing of silver from a solution of nitrate of silver, a somewhat troublesome process, and is subsequently, as a protection to the silver film, coated with a backing such as is used to protect the under surface of a mirror. Messrs. Baker, of Holborn, list a lamp produced on these lines, and are prepared to supply one suited for the voltage of the installation. This form of lamp forms an ideal light for the enlarging

lantern, as it is constant in luminosity, and is not of such an intensity as to be difficult to control.

During the present year (1922) the General Electric Company of Kingsway, London, has introduced a *Projector Type* of filament lamp. This is gas-filled, with the filaments so arranged in the form of a three-barred small grid that in a certain position of the lamp they can be made to combine and thus form a narrow band of concentrated light. This lamp can be worked satisfactorily upon an alternating current, and though only manufactured to run on a 100-volt circuit, it can be used in series with a carbon-filament lamp as a resistance in the case of the district supply being of higher voltage.[1] The author has had an opportunity of testing this new lamp and finds that it works very satisfactorily. It may also be used as a source of illumination in the optical lantern.

A **Mercury-vapour Lamp** consists of a tube of glass or quartz containing a small quantity of metallic mercury in vacuo. It is put in action by connecting it up with an ordinary lighting circuit perferably with direct current, upon which it works better and more easily than with an alternating supply, which requires the addition of some rectifying appliance. Tilting the tube so that the mercury runs from the positive to the negative pole completes the circuit, and causes a volatilization of the mercury which then acts as a vapour arc. The light obtained, when examined spectroscopically, consists of three bright lines, one in the yellow (5790–5760 A.U.), one in the green (5460 A.U.), and one in the blue-violet (4360 A.U.). Either of these bands can be cut out by the employment of filters, and thus a monochromatic light of restricted wave-length may be easily obtained. This point will be referred to again later on when dealing with filters. Even when used without any colour screen a mercury-vapour lamp is a very efficient illuminant, since, owing to the absence of red rays, the mean wave-length is less. The amount of current consumed in working is extremely small, and there is no waste of mercury, for as soon as the lamp is thrown out of action the mercury vapour becomes recondensed into liquid form. The tubes are fragile and require care, but apart from this a mercury-vapour lamp has a long and efficient life. There is but little heat in running, and owing to the wave-length of the light employed the resolution of an objective is considerably increased. When using the lamp it is very important that the negative wire should be connected up to the negative terminal of the lamp. Boil-

[1] A bulb for use on a 200–260-volt circuit is now supplied.

ing of the mercury as it retreats along the tube is an indication that the polarity is wrong.

Pointolite Lamp.—A new electric light, the *Pointolite lamp*, has been introduced recently by the Edison Swan Electric Co. This consists of a gas-filled glass bulb enclosing a small sphere of tungsten. When in use this diminutive ball becomes highly incandescent, and provides a light source of very small area. The Pointolite lamp is an enclosed tungsten arc, and is supplied with the necessary resistance for use on a direct-current supply of 100 to 250 volts. It is very easy to use, of long life, well maintaining its efficiency, and can be run without any special wiring. In action and principle this lamp has much to recommend it for photomicrography, and the writer cannot speak too highly of the capabilities of the standard 100-c.p. type. It provides a concentrated light of high actinic value, of extreme whiteness, and can be used in conjunction with colour screens for increasing or decreasing contrast, &c.

The Electric Arc for several reasons is perhaps the ideal source of light. It affords a small area of illumination of high candle-power, and if direct current be available works smoothly and without much attention. It is somewhat costly to run, as the resistance employed to bring down the voltage to, say, 50 or 60 volts consumes by far the larger amount of the current used. The great heat produced in working is also a disadvantage, and this will call for the provision of a water-cooling tank as a protection to the optical system of the microscope, &c. If armed with carbons of large calibre the amperage amounts to some 30 amperes or more, at which the lamp works will demand special wiring in the installation, although an arc lamp taking 4 to 5 amperes provides ample light for photomicrography, and this can be safely run off the ordinary house circuit.

Arc lamps are either automatic or hand-fed. If the former can be obtained to do its work well it is an obvious advantage to the worker to adopt this form. The carbons of an arc lamp are of different size according to their being used in connection with the negative or positive terminal. The positive carbon is the larger, and should be cored so as to burn more quickly than the solid negative one, and thus to ensure that the crater formed on the end of the positive carbon, the position of greatest luminosity, should not shift about. The carbons in most forms of lamp are placed one above the other, inclined at an angle of 30° from the vertical,

with the smaller negative carbon below and with its point slightly in front of the larger positive carbon. In this way the crater is drawn forward towards the microscope. Small arc lamps of the Lilliput type use cored carbons of small calibre arranged at right angles to one another. Upon the end of the positive, placed horizontally, the crater forms. The positive carbon is of 8 mm. diameter, and to ensure regularity of burning the negative carbon, which is placed vertically, is reduced in size to 6 mm. This difference in size of the two carbons is not, however, to be observed when using the lamp upon an alternating supply, as carbons of an equal size of 6 mm. calibre are found to work best under these conditions. An enclosed arc, although it performs better on an alternating current than the open variety, is not to be recommended for photomicrography, as the enclosing glass cylinder interferes with anything approaching critical illumination.

When using the electric arc or the oxy-hydrogen jet a *water-tank* should be employed to counteract the heat that is produced when they are in action. A thickness of water of some 3 in. in a glass cell, when an arc taking 30 amperes is being used, will be required to secure the safety of the microscope and the object to be photographed. With a 5-ampere arc a thickness of 1 in. in the tank will be ample. A solution of alum is sometimes recommended as a heat restrainer, but it is doubtful if it has much advantage over plain water. A weak solution of sulphate of iron seems to have decided heat-absorbing properties, and may be used. The water trough, which should have glass sides of good optical quality so as to minimize distortion when in use, should be placed in position between the collecting lens and the microscope.

Section IV.—The Treatment of Light

Light Filters.—The use of *light filters* has perhaps had a greater effect upon the technical quality of photomicrographs than any other influence, such as the introduction of improved optical apparatus, has been able to exert.[1] Imperfect correction of lenses, failing to secure sharpness of image, can be improved by the introduction in the optical system between the radiant and the substage condenser of a screen of green glass, which will be found to improve materially

[1] For a discussion of the sensitivity of plates to light of different wave-length see p. 172 *et seq.*

the resulting image. A control in contrast and improved resolution is the result of the introduction of a properly selected screen, and provided with a set of scientifically produced light filters, so as to be spectroscopically good, the worker at photomicrography has in his hands a very valuable addition—in fact an essential for the securing of the best results.

These screens or filters may be either employed in the form of coloured solutions of various strengths and composition contained in glass cells of the Leybold pattern, or they may be made of dyed gelatine mounted between two sheets of optically good glass. Both forms are effective, the latter perhaps being the more easy to use.

Screens may be made of coloured glass of such quality as not to refract the beam of light passing through them, but to obtain a set of filters of coloured glass scientifically prepared means considerable expense, and dyed gelatine mounted between good glasses forms an efficient substitute. Care must be exercised not to scorch up a gelatine screen when working with an illuminant giving out great heat. A set of nine filters, designed by Dr. Mees for photomicrography, and known as Wratten M filters, consisting of dyed gelatine, has been available since 1907. The period since their introduction has been long enough to test their capabilities, and they retain a prominent place in the estimation of experienced workers. Other sets are obtainable made under the supervision of Ilford, Ltd., and Sanger, Shepherd, & Co.

The following table applies to the M filters, which may be taken as representative of photomicrographic light-modifying screens.

Screen.	Visual Colour.	Spectral Transmission.	Exposure Factor for Arc.
A	Orange-red	5800 to red end	× 6
B	Green	4600–6000	× 12
C	Blue-violet	4000–5100	× 12
D	Purple	3800–4600 6400 to red end	
E	Orange	5600 to red end	× 6
F	Pure red	6100 to red end	× 8
G	Strong yellow	5100 to red end	× 4
H	Blue	4200–5400	× 12
K_2	Pale yellow	For orthochromatic rendering.	× $1\frac{1}{2}$

By using these filters in pairs as on p. 340 the spectrum can be

divided up into ten narrow sections successively from the extreme violet (4000 A.U.) to the deep red (7000 A.U.).

Screens.	Dominant Wave-length.	Colour.	Exposure Factor for Arc.
D and H	4500	Violet	× 64
C and H	4800	Blue	
B and C	5050	Blue-green	× 600
B and H	5200	Bluish-green	
G and H	5350	Pure green	× 1600
B and G	5500	Yellowish-green	× 64
B and E	5750	Greenish-yellow	× 250
A	6000	Orange-red	
F	6250	Pure red	
A and D	6610	Deep red	× 240

When using a panchromatic M-plate and employing an arc light, the relative increase of exposure, as compared with a correct exposure on the same plate with unscreened light, is indicated in the fourth column of the above tables. The factors there noted apply only to an exposure employing an arc light. They will be found to vary with different illuminants. Mr. J. H. Pledge, in a paper read before the Royal Photographic Society of Great Britain and published in the *Photographic Journal* for Feb., 1921, clearly indicates wherein the advantage of the employment of light filters in connection with photomicrography lies.

Monochromatic Screen.—The use of a monochromatic screen consisting of a green filter of narrow transmission in the yellow-green region of the spectrum has been mentioned earlier as improving the working, both visually and photographically, of an achromatic objective, bringing its working qualities nearly on a par with an apochromat. An effective green screen for the purpose has the power of absorbing wave-lengths of 4000–5000 and of 6400–7000, and confining the transmission band to the green and yellow regions of wave-length of 5400–6000, which is approximately that for which an achromatic lens is chiefly corrected.

Contrast.—To *increase* contrast a screen should be used complementary to the colour of the object. In photographing a blue-stained preparation use a red filter, in a red-stained one use a green, with a yellow stain use a blue, and if violet be the stain employed the correct contrast screen will be a yellow one.

To *decrease* contrast and increase detail the light employed should

correspond in colour with the transmission of the object, using light of a wave-length corresponding to the centre of its absorption band. In practice this rule is liable to modification. It is only when dealing with a faintly stained preparation that the maximum degree of contrast is required, and usually it is better, according to Pledge, to choose a screen transmitting rather to one side of the absorption maximum, otherwise the fine detail may be blocked up by an excess of contrast.

"If a colour is to be rendered as black as possible it must be viewed, or photographed, by light which is completely absorbed by the colour—that is, it must be viewed, or photographed, by light of the wave-lengths comprised within its absorption band" (C. E. K. Mees).

There is one important class of subject where this rule does not hold good. In the photography of insect preparations the aim is not to obtain contrast but to show detail, and to secure the maximum of this use a filter of the same colour as the object—an orange filter when recording a yellowish-red insect will be found to give satisfactory results.

It is a good rule to observe visually the effect of the filter that it is proposed to employ when photographing subsequently, and to choose such filter or combination of filters which will provide the best representation of the desired result.

It is essential to focus the object with the screen in position when an achromatic objective is used, but this rule does not apply when an apochromatic lens is employed, for with a lens of the latter type the image, whether viewed by white or screened light, will be equally in focus.

J. E. Barnard strongly favours the use of a liquid green filter known as Kettnow's. It consists of a saturated solution of copper nitrate mixed with a solution of chromic acid in water. This filter completely cuts out both the blue-violet and the red ends of the spectrum, and, by varying the proportion of the two solutions used in its composition, greater or lesser absorption of either end may be secured.

To obtain Monochromatic Light.—Monochromatic light approaching that of one wave-length only is somewhat difficult to obtain, though, when employing the mercury-vapour lamp, by the introduction of special filters it is easy to cut out the narrow bands not required, and to let pass the light of the wave-length we wish to use.

The following solutions will act as most efficient filters for mercury-vapour light.

(i) *To transmit Yellow Light*, 5790 to 5760 A.U.

Pot. bichromate	.. ..	15 gm.
Copper sulphate	.. ..	3·5 „
Sulphuric acid	.. ..	1 c. c.
Distilled water	.. ..	300 c. c.

(ii) *To transmit Green Light*, 5460 A.U.

Picric acid	.. ..	0·4 gm.
Copper sulphate	.. ..	3·5 „
Didymium nitrate	.. ..	15 „
Distilled water	.. ..	300 c. c.

(iii) *To transmit Blue Light*, 4360 A.U., and also the violet lines, 4070 and 4050 A.U.

Copper sulphate	..	1 gm.
Distilled water ..	..	225 c. c.
Ammonia, 0·880	..	75 „

For work with light other than that provided by the mercury-vapour arc, two separate solutions of tartarazine and acid green will make a filter having a transmission in the green in the region of 5300 A.U. of monochromatic character.

A saturated solution of picric acid is found to form a useful filter when employing achromatic objectives, seeing that it has a very definite absorption spectrum, and that the whole of the violet end from 3500 to 4700 A.U. is completely cut out. It transmits the yellow and green with a minimum loss of light.

It may be noted that fluid screens of certain spectral transmission and absorption would appear to increase the exposure necessary in photography less than similar gelatine screens with identical spectral transmission and absorption.

Dark Ground Illumination of Transparent Objects provides an effective display in which the material to be observed appears luminous upon a black field. This form of transmitted lighting has been secured in the past by the use of a spot lens or a Wenham paraboloid, and the more recent apparatus is constructed on somewhat similar lines. A substage condenser with a large working aperture is employed, and the light transmitted through it is blocked out in part by a central opaque stop so as to allow only the peripheral rays to pass in the form of a hollow cone impinging upon

and brilliantly illuminating the object. The central wheel stops, which fit into the back of the condenser, require careful adjustment, both as to correct centring and as to the size used, which should somewhat exceed the aperture of the objective employed. The success of the result depends upon this adjustment being correct. A Davis iris diaphragm, introduced between the objective and the nose of the microscope, will be found useful in cutting down the working aperture of a given objective, and thus helping to secure the correct relation between the size of the wheel-stop and the aperture of the objective. Should the amount of marginal rays transmitted by the condenser be greater than the object requires, indicated by a general haziness of the image, a diminution may be obtained by closing down the iris diaphragm of the substage. It is more particularly in low-power work that this form of lighting is to be recommended. A powerful illuminant is needed, and when photographing the result a comparatively long exposure will be required.

Section V.—Manipulative Details

The Arrangement of the Optical System employed in photomicrography on the base-board is indicated in the illustration of the horizontal camera (fig. 2, p. 327). A represents the position of the light, enclosed in a casing to prevent glare about the room where work is being carried on. B a collecting lens either consisting of a bull's-eye plano-convex lens with the plane surface towards the light, and provided with an iris diaphragm, or better, a Nelson condenser, which has less aberration than a single plano-convex lens. C a water cooling trough or liquid filter. D a second collecting lens with iris diaphragm. In some cases this additional lens, consisting of either two plano-convex components or a single biconvex lens, may be dispensed with. E the substage condenser fitted into the microscope, and provided with centring screws and an iris. F connecting cord between the fine adjustment and the long arm for focusing purposes. G light-tight connection between camera front and the microscope. H the long arm.

It is an essential that *the most perfect alignment* of the whole system—light, collecting lenses, substage condenser, objective, eyepiece, and the camera body—be obtained before any work is attempted. The provision of a triangular metal bar carrying saddle-back fittings to support the collecting lenses and the illuminant will allow of this strict alignment being easily obtained.

The Length of Exposure required to obtain a good photomicrograph depends upon several factors.

1. The rapidity of the photographic plate employed.
2. The intensity of the illuminant.
3. The efficiency of the collecting and condensing systems.
4. The presence or absence of a colour filter.
5. The numerical aperture of the objective (exposure varies as $\frac{1}{(NA)^2}$.
6. The magnification of the object upon the screen. (This depends upon various subfactors, such as objective and ocular, used.) Exposure varies as magnification^2; e.g. if a magnification of 25 diameters requires 4 sec., one of 50 will need 16 sec., and one of 100, 64 sec.
7. Extension of camera.
8. Magnifying power of the ocular.
9. The character as regards colour and density of the object photographed.

Upon the consideration of these factors must depend the correct exposure of the photographic plate. Various systems have been suggested, as indicated in the table dealing with colour filters, for arriving at an approximate estimate of the correct exposure. A consideration of these will be of help to the worker, but practice and experience only will enable him easily to decide the length of time required in the taking of the photograph. It is advisable that the beginner should obtain information from the record of a certain object on a plate exposed in strips. Having viewed the image focused on the ground glass and having decided from its luminosity to give it an exposure of say 10 sec., insert the plate, draw the dark slide, and give an exposure of half the time suggested as being correct, i.e. 5 sec. Push in the shutter of the dark slide a quarter and expose another 5 sec. Then push it in another quarter and expose a further 10 sec. Finally push it in another quarter and expose a further 20 sec. On development four strips of different densities will appear on the negative corresponding to the four exposures of 5, 10, 20, and 40 sec. From this experiment it will be easy to select the quarter best suited for the production of a positive print, and having determined that, make a note for future reference of the various factors entering into the production of the best result, e.g. object, magnification, light, condensing system, filter, objective, eye-

piece, camera extension, plate employed, length of exposure, and the result. These particulars should be carefully entered up in a numbered register of exposures, and will very soon form a basis from which a worker can expose a plate with certainty as to the result. The time spent in keeping such a record will be well repaid in the experience gained and the information provided upon which to estimate future exposures.

The Type of Plate recommended for photomicrography should be that having a fine grain, and this is usually found to be a feature of the slower kinds. It is generally advised that the plate must be backed as a precaution against halation, but with the Wellington anti-screen, the favourite plate of the author, this would seem to be unnecessary at any rate in the very large proportion of exposures. This plate, in addition to its qualities for clean working and good colour rendering in monochrome owing to its bathed character, is practically non-halating.

Panchromatic plates are required for certain subjects embodying colour not to be secured on an ordinary plate.

Cardinal Rules for Photomicrography.—

1. Never under-expose.

2. Use such a developer as will produce the result desired. *To secure contrast* use a metoquinol developer with possibly the addition of a little bromide. *To obtain softness* use a weak warm solution of pyro with potash and soda and no bromide. Rodinal or azol may be employed as alternative developers.

3. Avoid the use of a tank, and watch the building up of the latent image by means of a *safe* dark-room lamp. Carry on the development more or less according to the result desired. A prolonged development tends to harsh contrast in the final result.

4. In case of over-exposure care should be exercised not to curtail the development.

5. Try and produce a negative of such quality that it will not require any subsequent treatment in the way of reduction or intensification.

6. Use, apart from exceptional cases, one brand of plate, and master its working capabilities.

Section VI.—Stereo Photomicrography

In some cases a stereopicture, preferably a transparency, may be indicated, and this is more particularly the case when an object

has such a range of planes that the objective fails to secure a good representation. Stereo photomicrographs may be produced by means of a microscope having two tubes and two objectives, but an ordinary monocular microscope can be equally well used for the purpose, and is the form to be generally recommended. The variation of the two halves entering into a stereogram is secured in one of several ways.

Stereo negatives may be made of an object in a fixed position on the microscope stage, employing for one exposure half the field of the objective and for the second exposure the other half. This is easily effected by the use of a Jackson's stereo attachment—an inexpensive fitting taking at one end the objective and at the other end screwing into the nose of the microscope tube. An eccentric stop, either circular or rectangular, is provided by which one or other half of the objective is put out of action. Two quarter-plates are exposed, one securing the image obtained by the use of the left-hand half of the lens, and the other that of the image recorded when the right-hand half of the lens is used. Care must be taken to indicate on the plate the bottom of the object, and also whether the plate was that exposed to the left or right segment of the objective. This knowledge is of importance in securing the subsequent correct transposal of the positive results. Harshness and great contrast is to be carefully avoided, and consequently one should aim at somewhat over-exposed negatives, which invariably produce the most pleasing stereograms.

Another way to obtain stereo photomicrographs is to rule a line through the long axis of a half-plate camera focusing screen, and then upon that line drawn through the centre of the plate, $1\frac{1}{4}$ in. on either side of the centre of the line, make two marks. Upon the site of one of these focus a prominent feature in the centre of the object to be photographed, and make the exposure. Then shift the object so that the same prominent feature occupies the position of the second mark, carefully watching that the original base line is not displaced. An alternative plan is that in which the objective is slightly moved to such an extent on a sliding nose-piece as to secure successively on the two marks on the ground-glass focusing screen an image of the same position of the object, which remains stationary on the stage of the microscope.

In either of these ways a pair of stereo negatives may be made, either upon the two halves of a half-plate protected as regards the half not being exposed upon by the superimposing of a cardboard

screen or shutter, or two separate quarter-plates may be employed.

A transposal of the prints obtained with the usual separation of about $2\frac{1}{2}$ in. will secure, when viewed in the stereoscope, a picture with proper relief.

The best subjects for stereo photomicrography are those that take the form of opaque mounts, lighted by an oblique reflected illumination and not by transmitted light, since the shadow obtained by the oblique lighting adds materially to the stereoscopic relief. The most effective results are likely to be secured of objects subjected to the magnification of comparatively low-power objectives, such as 1 in. or 2 in., though at the same time the author has been able to produce a satisfactory series of stereos of diatoms specially mounted as opaque objects in which the depressions and eminences on their surface, so difficult to record when viewed by transmitted light as transparent objects, have been secured by the employment of an oblique form of reflected lighting, and an objective of higher power.

Appendix

Examples of Photomicrography

(See Plate)

1. Section of Lyginodendron in Coal Shale × 1·5. Cooke 4·1-in. photographic lens *f*/16; no microscope and no eye-piece; Spitta green filter; 25-c.p. silvered metallic-filament lamp; Wellington anti-screen plate; 60 sec. exposure.

2. Face of Dinopis Spider ♀ × 7. Aldis 3-in. photomicrographic lens *f*/8; no microscope and no eye-piece; 25-c.p. silvered metallic-filament lamp; Wellington anti-screen plate; 3 min. exposure.

3. Pollen of Hollyhock × 46. $\frac{2}{3}$-in. Swift panaplanatic objective; No. 4 eye-piece; Nernst $\frac{1}{4}$-ampere lamp; reflected light; Imperial special rapid backed plate; 60 sec. exposure.

4. Pseudo tracheæ on Tongue of Blow-fly × 150. Reichert 4-cm. objective ($\frac{1}{2}$ in.); No. 2 eye-piece; 25-c.p. silvered metallic-filament lamp; no filter; Wellington anti-screen plate; 2 min. exposure.

5. Hairs on Wing of House-fly × 243. $\frac{2}{3}$-in. Swift panaplanatic objective; No. 4 eye-piece; Nernst $\frac{1}{4}$-ampere lamp; transmitted light; blue glass filter; Imperial special rapid backed plate; 12 sec. exposure.

6. A Coal Fossil Fern (Stauropteris), Section through Petiole × 22. 2-in. Watson parachromatic objective; No. 1 eye-piece; 25.-c.p. metallic-filament silvered lamp; Spitta green filter; Wellington anti-screen plate; 3 min. exposure.

7. Human Flea ♂ × 15. 2-in. Watson parachromatic objective; No. 1 eye-piece; 25-c.p. metallic-filament silvered lamp; Spitta green filter; Wellington anti-screen plate; 60 sec. exposure.

8. Group of Diatoms (Hungary) × 40. $\frac{2}{3}$-in. Swift panaplanatic objective; No. 2 eye-piece; Nernst $\frac{1}{4}$-ampere lamp; transmitted light; green filter; Imperial special rapid backed plate; 12 sec. exposure.

9. Diatom (*Heliopelta metii*) × 350. $\frac{1}{6}$-in. Watson holoscopic objective and eye-piece; oxyhydrogen light; Sanger-Shepherd green filter; Marion's Isoplate; 90 sec. exposure.

10. *Trypanosome Lewisi* in Blood of Rat × 1000. $\frac{1}{8}$-in. apochromatic objective; projection 4 eye-piece; Nernst 1-ampere lamp; Wratten B screen; Ilford chromatic plate; 25 sec. exposure. (Negative by Dr. Duncan Reid.)

11. Phagycytosis (Amœbæ and Bacteria) × 1000. $\frac{1}{8}$-in. apochromatic objective compensating 8 eye-piece; Nernst 1-ampere lamp; Wratten K_3 screen; Ilford chromatic plate; 8 min. exposure. (Negative by Dr. Duncan Reid.)

12. Hairs of Larva of Dermestes Beetle × 100. Reichert 4-cm. objective; No. 1 eye-piece; 100-c.p. Pointolite lamp; Wellington anti-screen, backed plate; 25 sec. exposure.

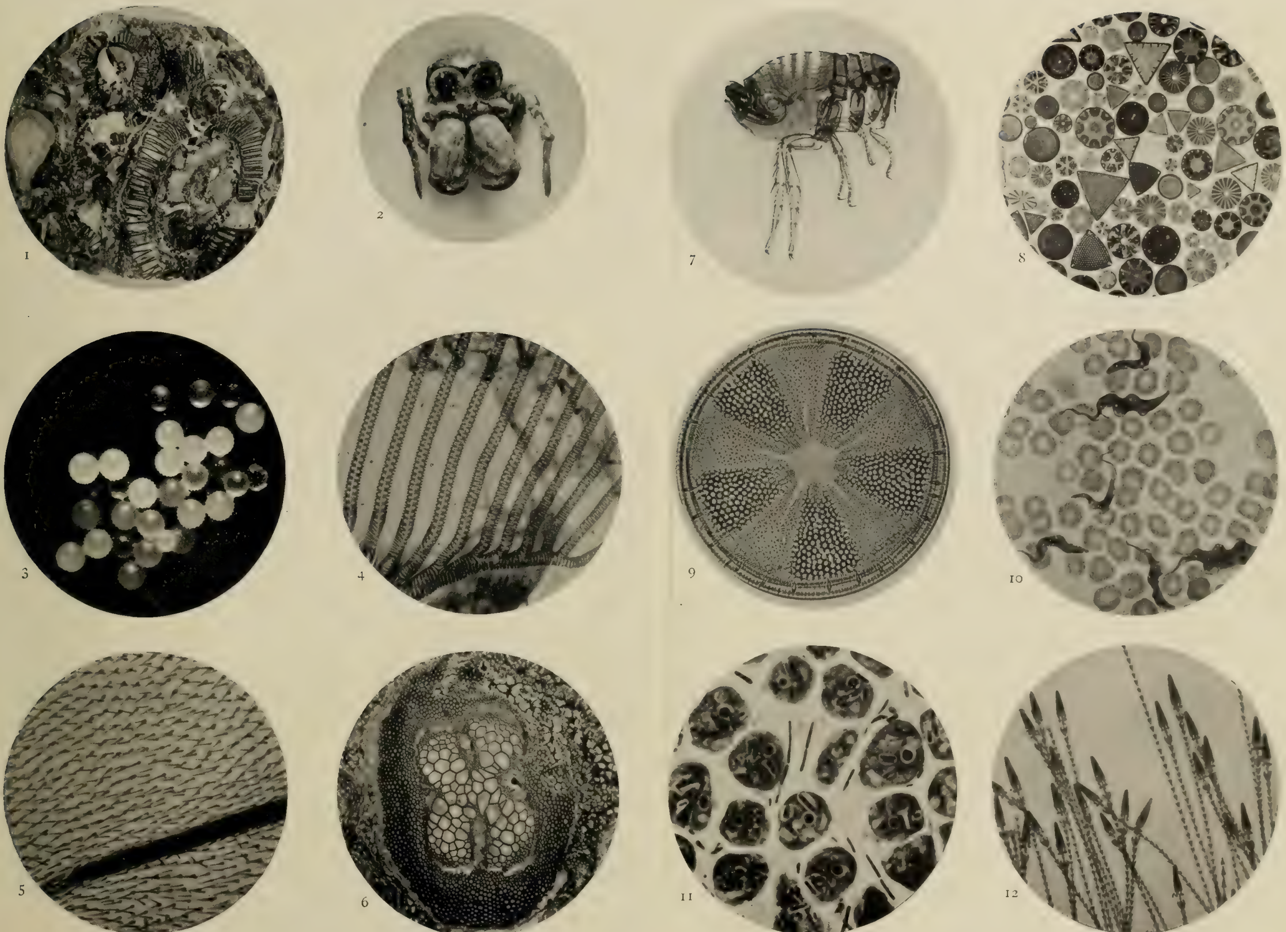

Fig. C.—Examples of Microphotography

Facing p. 348

CHAPTER IX

Photographic Surveying

Section I.—Photographic Surveying

Historical.—A photograph shows the objects which appear upon it in a definite relationship to each other. If certain factors be known, this relationship can be converted into angular measurement, and we can, upon a map or plan, draw rays from the position at which the camera was used to the various objects whose positions we desire to establish.

In order to do so it is necessary to know the equivalent focal length of the camera lens and the direction of some one point, which appears on the photograph, from the position of the camera. The camera is used, in fact, as a theodolite or plane-table for recording angular measurements, and it is obvious that vertical angles may be measured on the plate as easily as horizontal. This method of survey is now generally known as photogrammetry.

Colonel Laussedat of the French army was the pioneer in the application of photography to surveying, and his books treating of his experiments, and his theoretical investigations from 1853 to 1900, remain the most widely consulted authorities. It is natural, for reasons which will appear later, that photographic surveying should develop more quickly in mountainous and well-marked country; we find accordingly in the Alpine regions of Europe and in the mountain chains of North-West Canada that the largest areas have been photographically surveyed.

The standard work in English, *Photographic Surveying*, is from the pen of Captain Deville, Surveyor-General of the Dominion Lands of Canada.

Supposing now that two photographs are taken of the same area, from different positions which are plotted on the map. If the area in question is completely covered on both plates, we may draw rays from the two positions to each identifiable point and object

in turn until we have a complete survey. The plotting of detail in this manner is generally called ground photo-topography.

In order to ensure covering as much ground as possible on one plate, it is advisable generally to use the camera from the highest possible points. It is natural then to find that since the earliest days of photogrammetry efforts have been made to mount the camera in balloons or kites. Both are unsatisfactory and largely uncontrollable. Nevertheless, certain plans were made from plates so exposed during military operations both in Europe and America.

The advent of the aeroplane and the enormous importance of maps for the operations of war, gave this side of photographic surveying a great impetus. Surveying from air photographs is now commonly known as air photo-topography.

Whether the photograph be taken from the ground or the air, measurement on the plate will give us angular measurement from the camera position, but not distance or range. The measurement of distance of any point from the camera must indeed wait until the position of that point is determined by intersecting rays from two or more camera positions.

It is, however, precisely in the identification of points on different photographs, and in the subsequent measurement and plotting, that the difficulties and delays of photo-topography occur.

These difficulties can be largely remedied by using the stereoscopic powers of human vision. Professor Pulfrich, of Jena, has designed a stereoscopic comparator for use with photographic plates taken at both ends of a measured base, and by its use the position and height, relative to one end of the base of any object common to both photographs, may be established.

In this connection Captain von Orel, of the Austrian army, has devised a " stereo autograph " which plots mechanically as it follows the adjustment of the stereo comparator on each point in turn. This process is known as stereo photogrammetry or stereo photo-topography, accordingly as one emphasizes the idea of measurement or of detail plotting.

Finally Professors Hugershoff and Cranz have recently manufactured and patented an autocartograph for automatic plotting from air photographs used stereoscopically.

Photographic surveying depends, like any other survey method, upon certain principles, and must follow upon the lines which experience dictates. It is governed further by the perspective laws which define the relationship of line to line and plane to plane, and it

necessitates certain special features in the design of the photographic instruments employed.

These preliminary matters will then form the first part of this chapter, and will be followed in turn by photogrammetry, ground photo-topography, air photo-topography, and stereo photo-topography.

Survey Principles.—It is a fundamental survey principle that no considerable area can be mapped without a control or skeleton of positions determined relatively to each other with precision.

The first step in building up this control is to measure a base—usually of some miles in length. Upon this base and extending from it a triangulation covers the area to be mapped, and is usually connected in its extension to other bases, which serve to maintain its rigidity. The first or primary triangulation usually includes points at distances of some 30 miles from each other, and may be considered to define the distance between any two points to within 1:50,000 of the true length. The initial triangulation is then broken down and amplified with instruments of less precision until the area includes a fixed point every few miles.

Topographical methods of survey start from this control, and, whether they consist of traversing, tachyometry, plane tabling, or chaining, seldom escape errors of the order of 1 : 1000. Photogrammetry and photo-topography are also of this order of precision.

A trigonometrical framework is then an essential, and its existence will be taken for granted in the future.

It will be as well here to define the special terms which will be used in this chapter.

Definitions.—

Principal Point.—The foot of the perpendicular from the lens to the plate.[1]

Optical Centre.—The centre of the exposed portion of the plate as defined by the intersection of lines joining collimating points.[2]

Principal Plane.—The plane passing through the lens, the zenith, and the principal point.

Principal Line.—The trace of this plane on the photograph.

Horizon Trace.—The trace of the horizon on the plate.

Map Plumb-point.—The point vertically below the camera on the plane of the map at the moment of exposure.

[1] This point should, in a properly adjusted camera, coincide with the intersection of the optical axis of the lens and the plane of the plate.

[2] This should coincide with the principal point.

Photo Plumb-point.—The image, on the photograph, of the map plumb-point (this is also the vanishing point of verticals).

Vertical Photograph.—One taken with the optical axis vertical.

Horizontal Photograph.—One taken with the optical axis horizontal.

Rectification.—The process of restoring a tilted image to its correct shape on a horizontal plane.

Perspective Laws.—A photographic plate is obviously a perspective view of the landscape or object it represents. The simplest case to consider is that of a perspective view of a plane upon a second and parallel plane. In this case we get a copy of the original which differs from it only in the matter of scale.

If we call R the representative fraction of the scale of the photograph, then $R = \frac{f}{h}$, where f is the focal length, and h the distance of the photographed plane from the camera. Such a view would result from photographing a vertical cliff on a vertical and parallel plate, or from photographing a flat plain upon a horizontal plate from an aeroplane. The latter case is aimed at, but rarely achieved, in the air photo-topography of a flat region.

In all other cases then these parallel lines on the ground must meet at some vanishing point on the perspective. Vertical and parallel lines on the original will meet at the zenith or nadir in the perspective, horizontal parallel lines on the horizon line.

The value of vanishing points in plotting the topography will be referred to later.

There are four perspective laws which are of particular moment to the photo surveyor, and which will be briefly enunciated.

1. A straight line upon any plane remains a straight line upon any perspective view of that plane.

2. The cross ratio of any four points ABCD on a line AD remains the same on any perspective of that line. (See figs. 1 and 2.)

The value of this law lies in the assistance which it gives to plotting. Suppose that four points (ABCD) lie upon a plane and have been plotted upon the map, and that the images of these points (*abcd*) are identifiable on the photograph of that plane. Then any other points which lie in the same plane may be plotted in the following manner.

On the photograph draw rays from *a* to *b*, *c*, and *d*, and to any other points whose positions have to be plotted. Place across this

pencil of rays a strip of paper in any position and mark upon it the spots where the lines *ab*, *ac*, *ad*, &c., cut the paper edge. Place this same strip of paper on the map across the pencil AB, AC, and AD in such a manner that the marks on the edge of the paper lie upon these lines. Now transfer to the map those points through which rays from *a* passed on the photograph to the unplotted but desired points, and draw rays from A through these points.

These rays will pass through the correct positions on the map.

Repeat the process with B, C, or D as apices of the pencil of

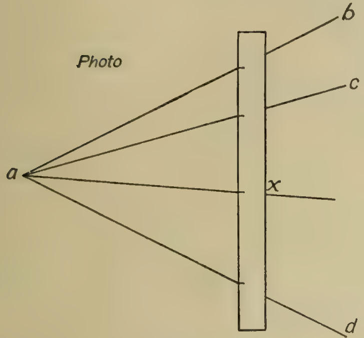

Fig. 1

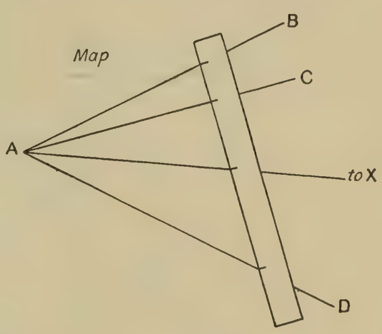

Fig. 2

rays, and the intersection of the plotting rays will give the desired information.

3. If we consider a figure upon a plane we may secure identical perspective of that figure upon a variety of other planes, but all these perspective planes will intersect each other and the plane of origin in one straight line called the perspective axis (see fig. 3).

4. The perspective centres from which these identical perspective views are projected must lie in the same plane, which is perpendicular to the perspective axis.

The value of laws 3 and 4 lies chiefly in the plotting from air photographs of flat regions in cases where those photographs were not truly vertical, but tilted through a known angle, and they enable us to design photographic or optical instruments by means of which this rectification may be carried out, with reference both to scale and perspective.

Space forbids a more thorough examination of perspective laws, but they may be found clearly explained and illustrated in *Photographic Surveying*, by E. Deville, Surveyor-General of Dominion

Lands (Ottawa, 1895), and in *Mapping from Air Photographs*, by Lieut.-Colonel M. N. M'Leod, D.S.O., R.E. (H.M. Stationery Office).

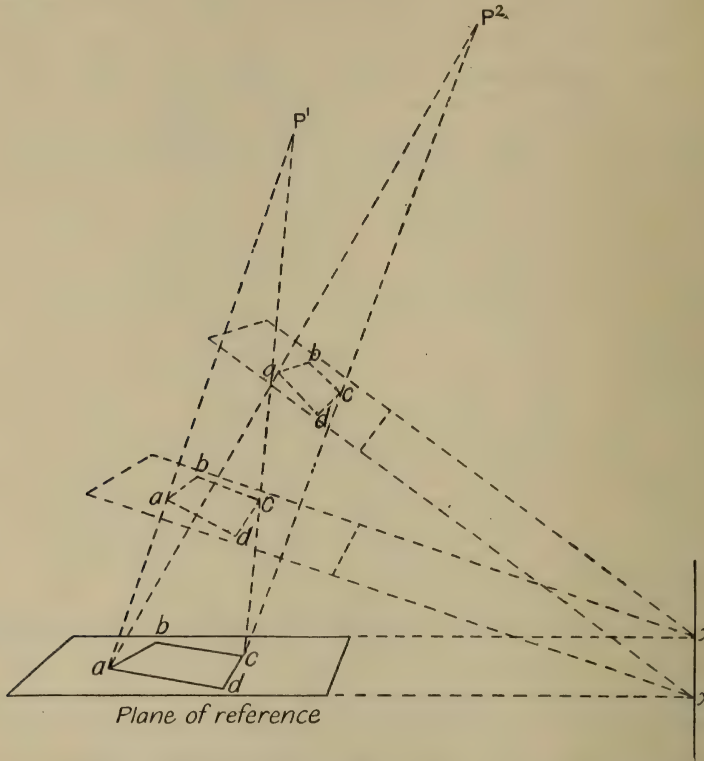

Fig. 3

Surveying Cameras.—In order that the angular measurement given on the developed plate may be utilized it is necessary to know the focal length of the camera. It is true that if, on the plate, the images of a sufficient number of fixed points appear, plotting may still be done, for the focal length may be deduced, but the additional computation is obviously undesirable.

The plates or films employed should be kept rigidly in the focal plane, and at a distance from the back nodal point, measured along the principal axis, equal to the equivalent focal length.

All cameras specially constructed for surveying make special provision for pressing the plate firmly against a metal rim in the camera. The principal point is important in plotting, and for this

reason collimating marks are made at four points in the metal rim, such that the lines joining them (and their images on the plate) will define the principal point.

It is advisable to add further marks on the rim defining definite lengths, from which the scale and freedom from distortion of any print or enlargement may be verified. In order to prevent reflection inside the camera it should be painted a dull black.

Halation introduces grave troubles in both ground and air photo-topography, and is minimized by backing the plates.

The question of lenses is naturally one of much importance. Distortions due to the lens may be to some extent allowed for if a careful calibration is made, but it is essential to eradicate any factor which implies extra calculation or time.

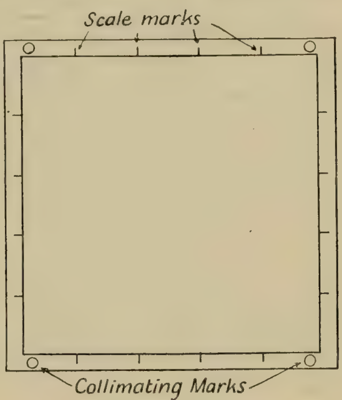

Fig. 4

It is advisable to cover a large angular field and to maintain a uniform definition over the plate.

Spherical and chromatic aberration must be negligible. So far the characteristics of a suitable camera for photo-topography are common to ground and air work. Certain further factors, however, exist in each case, but indicate different solutions. In the first instance ground photo-topography permits of relatively long exposure. Air photo-topography, depending upon plates exposed from an aeroplane which may be travelling 150 ft. per second, does not. For ground work the camera tripod must be rigid and yet light and portable.[1] For all photographic surveying it is important to define the plane in which the plate was at the moment of exposure, but for horizontal photographs the camera can be levelled easily enough to ensure of the verticality of the plate, whilst for vertical photographs there is at present no means of ensuring the horizontality of the plate.

It is more than likely that some means of controlling the camera in an aeroplane will be discovered soon. When this discovery has been made, not only will much of the difficulty of air photo survey

[1] Captain Deville recommends the use of a net slung between the legs of the camera tripod and weighted with stones, adding rigidity and steadiness.

be eliminated, but the way will be opened to the stereoscopic examination of the plates and to photo contouring.

Photography from the air, hindered by the rapidity of movement and vibration of the plane, introduces special difficulties which are dealt with in the chapter on aeronautical photography, and need no further mention here.[1]

A brief note on models of cameras for ground photographic survey is, however, necessary. The first experiments in photographic surveying were made with ordinary cameras which included no special features of adjustment or optics. A plumb-bob was sometimes hung in the field of view—giving a parallel to the principal line and a perpendicular to the horizon. Plates exposed from such cameras were not, generally speaking, truly vertical, and the subsequent operations of plotting were burdened with additional calculations.

No extensive survey would be carried out with such a camera to-day, because there are already on the market a variety of well-designed survey cameras to choose from. Almost all of these are made for the vertical position of the plate only, although in one or two models a rising front is added. Some are designed with a theodolite mounted on top of the camera or eccentrically at one side. In other designs an eye-piece can be inserted in the centre of the focusing screen in such a manner that the cross threads define the principal point, and that a telescope is formed with the object glass.

All have arrangements for levelling, and some have special fine motion adjustments in the plate-holder to allow of adjusting the principal and horizontal lines. It is a common feature of all designs to allow of pressing the plate firmly into its position for exposure in order to preserve a constant focal length, and practically all models arrange for collimating marks on the plates (after exposure) to allow of reconstructing the principal point.

Captain Deville in his book on photographic surveying gives a detailed description of many of these models. It is noteworthy that the model designed by him for the photographic surveys in Canada fits upon the theodolite stand, and is used in conjunction with an ordinary theodolite.

It is probably wise to make no attempt to combine the two instruments. Each has its own special features and may have to be used separately, whilst on the score of portability a few small and separate parts are preferable to a single and more cumbersome

[1] See p. 413.

whole. Cameras which are combined with instruments for angular measurement are generally called phototheodolites. They are mostly of French, German, Austrian, and Italian manufacture, although one good model—the Bridges Lee—is made by Cassella & Co., London.

So far no mention has been made of the panorama camera. Martens, of Paris, was the first to manufacture such an instrument. Panorama cameras offer an obvious advantage in the speed and simplicity of obtaining a complete tour of the horizon. Up till comparatively recent times they were not employed in any important survey, because they were not judged to be sufficiently precise. The rotation of the lens and the maintenance of a correct focal length (or radius of the film) introduce obvious sources of error.

Very interesting details of a reconnaissance survey in Alaska, carried out by a combination of plane-table, panoramic photography, and barometric heights, were published in 1917 by James W. Bagley in *Bulletin* No. 657 of the United States Geological Survey, under the title " The Use of the Panoramic Camera in Topographical Surveying ".

Section II.—Photogrammetry

It is advisable before proceeding to a study of photo-topography to consider the accuracy with which angles can be measured from the plates.

The process of measuring angles or of measuring the co-ordinates from which angles may be calculated is generally known as photogrammetry. Hitherto photogrammetry has played little part in the actual topography, which is usually done graphically. On the other hand, it is sometimes desirable to measure the angles to a few points with a precision unobtainable by graphic methods, in order to reset the camera position, to fix additional control points, or to check the interior adjustments of the camera.

The accuracy of the bearing of any point as calculated from the co-ordinates of its image measured on the plate, depends upon three factors:

(*a*) the accuracy of measurement of co-ordinates of the image;
(*b*) the accuracy of the measurement of the focal length of the camera;
(*c*) the accuracy of establishing the coincidence of the principal point and the optical centre of the plate.

Co-ordinates are measured in a simple form of comparator,

shown in fig. 5. Here 1 is a microscope with a measuring scale in the field of view. The corner of this scale is set against the point whose co-ordinates are to be measured, and the actual readings are those where the arms of the scale cut the lines of a grid which is either printed on the film of the negative from an engraved glass plate, or engraved on a sheet of celluloid superimposed and in close contact with the negative.

The arms of the scale must be parallel and perpendicular to the grid lines, and to effect this the plate-carrier 4, in which the plate 3 is shown, can be rotated about its centre. The central point of the grid is placed as nearly as possible in coincidence with the principal point, and the grid laid parallel to the principal line and the horizontal trace. The microscope has a movement in two directions, along its carrier, 2, in one sense, and with the carrier on the frame in the other.

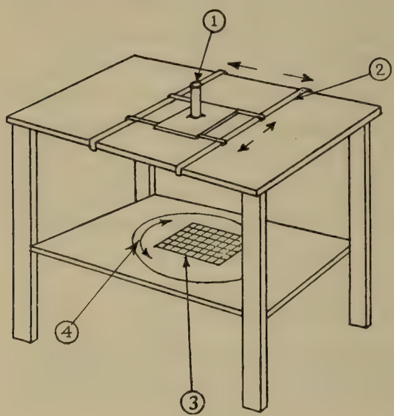

Fig. 5

Providing that we choose a clearly defined image, such as that of a star, there is no difficulty in measuring its co-ordinates on a plate with a probable error of 0·001 of an inch.

In practice, however, the photo surveyor will find few images which can be measured with this refinement. In bisecting an object with a theodolite one is helped by a judgment of its centre and of its highest point by various factors of light, shade, and background. These factors may be very poorly reproduced on the negative. With indefinite objects, errors of some hundredths of an inch in measuring the co-ordinates are common.

The focal length[1] of the camera f is equal to $\dfrac{d}{\tan\alpha}$ (see fig. 6), which in a perfect lens would equal $\dfrac{d}{\tan\alpha'}$, but in practice will never do so perfectly. f consequently varies[2] from place to place on the

[1] See Chapters II and III for a discussion of optics and lenses.

[2] For the magnitude of the changes in f due to various lenses, see *Ueber Photogrammetrie aus Luftfahrzeugen*, Pulfrich (Jena, 1919).

plate. In some lenses the variation is very small, in others it may assume some hundredths of an inch.

Cameras are, naturally, affected by changes of temperature, which cause differences in the focal length and in the relative positions of lens and plate.

With carefully constructed, calibrated, and used surveying cameras the net results of these errors should be small. They imply, however, that an uncertainty of the order of 0·01 of an inch may be expected.

The same order of error will be found between the position of the principal point and the optical centre on the plate. The principal point is found by joining the collimating marks photographed on

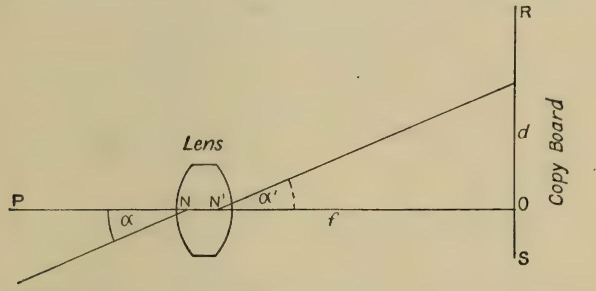

Fig. 6

the plate. So far these are not generally perfect in shape or in definition, and do not allow of a greater accuracy than that given above.

In ground photo-topography the bearing (θ) of any particular point on the plate (with reference to that of the optical centre) is $\tan^{-1}\frac{x}{f}$, where x is the abscissa of the image (measured on the horizon trace) and f the focal length.

If x and f be regarded as variables, we get

$$d\theta = \frac{dx}{f}\cos^2\theta \text{ with respect to } x,$$

$$d\theta = \frac{df}{2f}\sin^2\theta \text{ with respect to } f.$$

These two equations will give an idea of the errors likely to be met with. Suppose $f = 8$ in. and $\theta = 25°$, and let dx and df each equal 0·01 in.

Then $d\theta$ (the error made in determining the bearing) will equal

the square root of the sum of the squares of the errors due respectively to dx and $d\theta$, or an angle of the order of 5 minutes.

It must be understood that the above deals only with the absolute determination of angles.

The problem is naturally different when we are measuring the position of a well-defined object relatively near to one, two, or more similarly sharply defined and previously known objects.

In photogrammetry as applied to air photo survey, we may find errors of a larger order still, owing to the following factors:

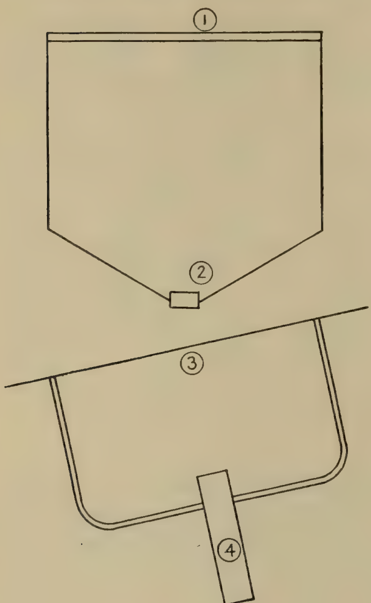

Fig. 7

1. Added uncertainty in recording the temperature and in allowing for its effect on the focal length.

2. Less precision in fitting the plate into its true position for exposure, as cameras for use in the air have to be designed for the rapid automatic changing of the plate.

3. The movement of the aeroplane during the period of exposure, which will be the resultant of the ground speed and any banking (for stability or for turn).

This factor is too involved a one for discussion here, but the following will illustrate the class of error to be expected with a focal-plane shutter. Suppose the ground speed to be 150 ft. per second with a total exposure of $\frac{1}{15}$ of a second, the camera will have moved 10 ft. during this time. On the other hand, if a between-the-lens shutter is employed with a period of exposure of about $\frac{1}{150}$ of a second, errors due to movement of the plane may be made negligible.

Without more experience than we now possess, it is impossible to assess definitely the magnitude of the total errors to be expected. It is clear that they may be serious, and it follows that photogrammetry, as explained above, can justify itself only if the interior adjustments of the camera have been accurately determined.

Photogrammetry takes another form, however, in the "Koppe"[1] design of plate theodolite which measures, not co-ordinates, but angles on the plate. This theodolite is attached to a camera exactly reproducing the interior adjustments of that from which the exposure was made in the first instance.

Here 1 (fig. 7) is the plate on which measurement is made. In the case of an air photograph, the plate is inserted at the angle of tilt at which exposure was made. 2 is the lens with which the original photograph was taken (or one identical with it), 3 the pivot of the Koppe theodolite, and 4 its telescope.

The trunnion axis of the theodolite must be in the plane of the trace of the horizon on the negative.

The advantage of this instrument lies in the fact that it automatically eliminates errors due to the lens distortion.

In this country we have had no experience with the Koppe plate theodolite for topographical purposes.

It appears to have considerable advantages, both of additional accuracy and of saving of time.

Section III.—Ground Photo-topography

The Field Work.—The first step in the field work is the selection of camera stations. Ultimately every feature of the whole of the area to be surveyed should appear on two plates exposed at two different stations. Generally speaking it is not difficult in mountainous country so to cover the greater part of the area in question. It is difficult, however, to make sure of complete photographic material. If there exists any map, however rough, a preliminary selection of stations should be made upon it. Generally speaking the positions chosen should be as commanding as possible, but this is not an invariable rule, for it is often necessary to choose a comparatively low station in order to secure some special view.

On arrival at the station the first duty is to secure with the theodolite or the plane-table the data from which to resect the camera station. At the same time rays should be observed or drawn, and the vertical angles measured, to a few important points which will appear on the photograph.

These observations serve to check the interior adjustments of the camera and its levelment, and also the plotting on the map.

The camera is now substituted for the theodolite and levelled.

[1] See *Ueber Photogrammetrie aus Luftfahrzeugen*, Pulfrich (Jena, 1919).

The view should be looked at in the view-finder, or with reference to "finder" lines on the camera-box, to make certain it is what is wanted.

The carrier is now inserted and the plate exposed.

Mention must here be made of the period of exposure. It is usual in ground photo-topography to use orthochromatic plates with an orange screen. The proper stop to use will be, as a rule, determined for particular dates, altitudes, and hours of the day, with a certain latitude left to the actual operator in case of backgrounds and exceptional lights.

In order to avoid any difficulties of identification in the plotting office, both theodolite (or plane-table) observations and the exposed plate should be marked with a definite station number, and a further and most valuable aid is a named and annotated panoramic sketch of the area photographed.

It is an important feature of the field work to test the positions on the plate of the horizon trace, principal line, and their intersection, the principal point, which are normally found by joining collimating points photographed on to the plate.

The simplest way to do so is to choose some 3 or 4 points fairly near in the same horizontal plane as the object-glass of the camera. These points should be selected with the aid of a carefully collimated theodolite, set up with its axis in the desired plane.

These points are photographed in the camera in its normal position, and in a position in the same plane, but at right angles to the first, thus defining two lines at right angles to each other, which in the normal position represent the horizon trace and the principal line.

Plotting.—One of the advantages of ground photography is, that the survey of detail is done in the office, and is therefore independent of the weather. It is a survey from perspectives of nature. In considering this survey it is unnecessary to deal with cases in which the photographs were taken with cameras which were not specially designed for the purpose. Such photographs offer interesting problems, but are of little practical value. It is, however, possible to deduce from any photograph the focal length and the position of the principal point, given the images of 3 points whose horizontal positions are already known, and of 2 points whose altitudes are known.[1]

We will therefore consider only the normal procedure of plotting ground photo-topography, when the camera constants and the position of the camera are known, and when the photograph contains

[1] *Vermessungskunde*, Vol. II, Jordan (1908).

the image of at least one point of the triangulation. Consider a photographic plate with upon it the image of one trig point B (fig. 8),

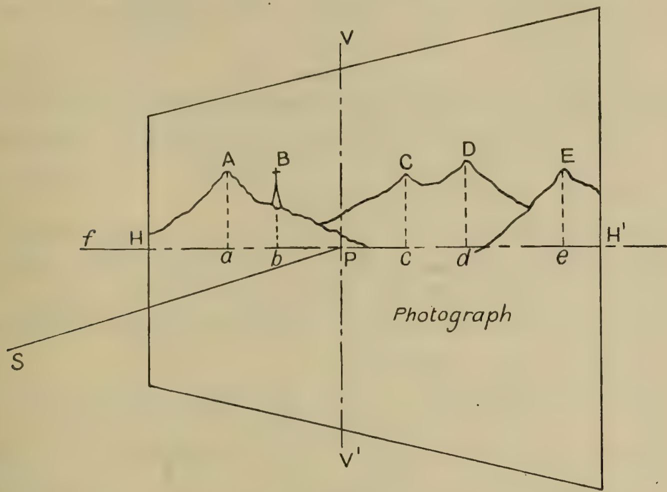

Fig. 8

and four other unknown points, whose positions are to be surveyed.

S is the position of the station occupied;

P, the principal point;

SP, the focal length (f);

P*a*, P*b*, P*c*, P*d*, and P*e* the abscissæ; and

*a*A, *b*B, *c*C, *d*D, and *e*E the ordinates of points A, B, C, D, E.

HH′ is the horizon trace, and VV′ the principal line.

SPH, SPH′, SPV, VPH, and VPH′ are all right angles.

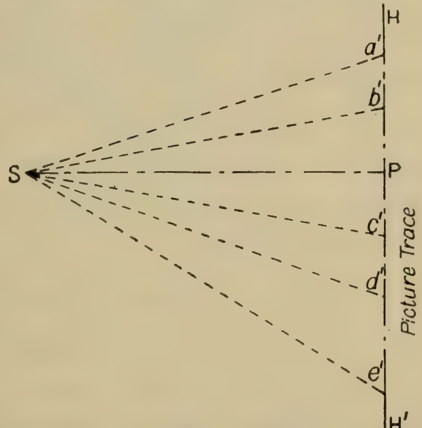

Fig. 9

Take a piece of tracing-paper and on it draw two lines at right angles in the form of a T-square[1] representing HPH′ and SP (fig. 9).

[1] It is as well to have traces already printed with the focal length (f) correct for the camera in use. In such a case, however, the length SP(f) must be checked before use to guard against the expansion and contraction of the paper.

Mark a point on HPH′, b', so that Pb' on the tracing-paper is equal in magnitude and sign to Pb on the photograph.

Join Sb' and produce it. Now lay the tracing-paper upon the compilation diagram. On this compilation will already appear the plotted positions of the trigonometrical points, and also the positions, trigonometrically fixed, of the camera stations. Place a needle through the position of S on the tracing-paper and S on the compilation.

Revolve the tracing-paper till Sb (produced if necessary) falls over the position of B (the trig point).

Keeping the tracing-paper in this position, prick through positions defining HH′ and P on the tracing-paper. Now remove the tracing-paper and join HP and H′ in fine but firm pencil. Place a strip of paper on the photograph and mark upon its edge the positions on HPH′ of a, P, c, d, and e.

Transfer these positions to HH′ on the compilation and draw rays from S through these points. These rays will pass through the positions of A, C, D, and E on the compilation, but it must be remembered that the compilation will be on the scale at which the map is to be plotted, whilst the construction lines are on the scale of nature. Hence A, B, C, and D may fall on either side of HH′.

To complete the horizontal survey each point must be photographed from two points, the distance between which acts as a base. It is important, in graphic methods such as these, that the angle of intersection of the two defining rays should not be less than 20°.

In fig. 10 A′ is the position of A on the map as found by intersection. AA′ is the height of A above the horizon (if we neglect the effect of curvature and refraction); aa' is the ordinate (y^a) on the photograph; S, P, and HH′ are as before, the station, the principal point, and the horizon line.

$$\text{Then } AA' : aa' = SA' : Sa',$$

$$\text{or } AA' = \frac{aa' \times SA'}{Sa'};$$

but Sa' and SA′ can be measured from the compilation diagram; aa' can be measured from the photograph.

The foregoing is not, however, quite true because of curvature and refraction. Owing to the curved surface of the earth any point A at some distance from S will appear lower than it actually is, and this correction, which in all cases increases the height as determined above, increases as the square of the distance SA′.

Refraction, on the other hand, diminishes the height of A as determined by fig. 9, but, as refraction is of a smaller order than curvature, the correction invariably increases the height.

Tables giving the value of this correction are to be found in any book on survey.

We will now suppose, referring to fig. 8, that A, B, and D are all trig points, and that the principal point and principal line are known,

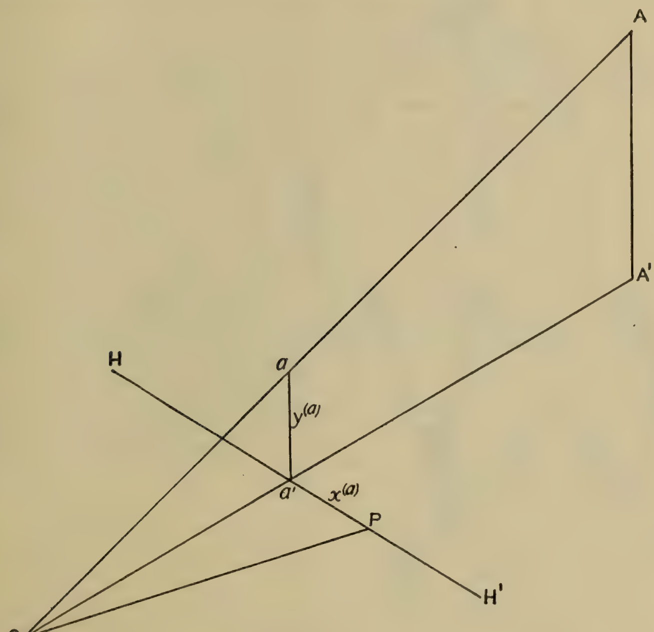

Fig. 10

but not the position of the camera. We may then, by drawing the rays S*a*, S*b*, and S*d* on the tracing and by moving it about until these rays pass over the points A, B, and D, find the position S on the plan representing the camera station. Alternatively, if we know the position of the camera station we may check the position of the principal point as follows:

Draw on the map the rays SA, SB, and SD, and across the pencil of rays so formed place a strip of paper on which the positions of *a*, *b*, *d* on the photo horizon line have been marked. Where these ticks fit on the rays SA, SB, and SD, make marks, and join these marks to form the line HH′. A perpendicular from S, of length *f*,

intersecting this line in P, defines the position of the principal point.

There sometimes occur cases in which the photograph includes the view of some horizontal plane, such as the surface of a lake,

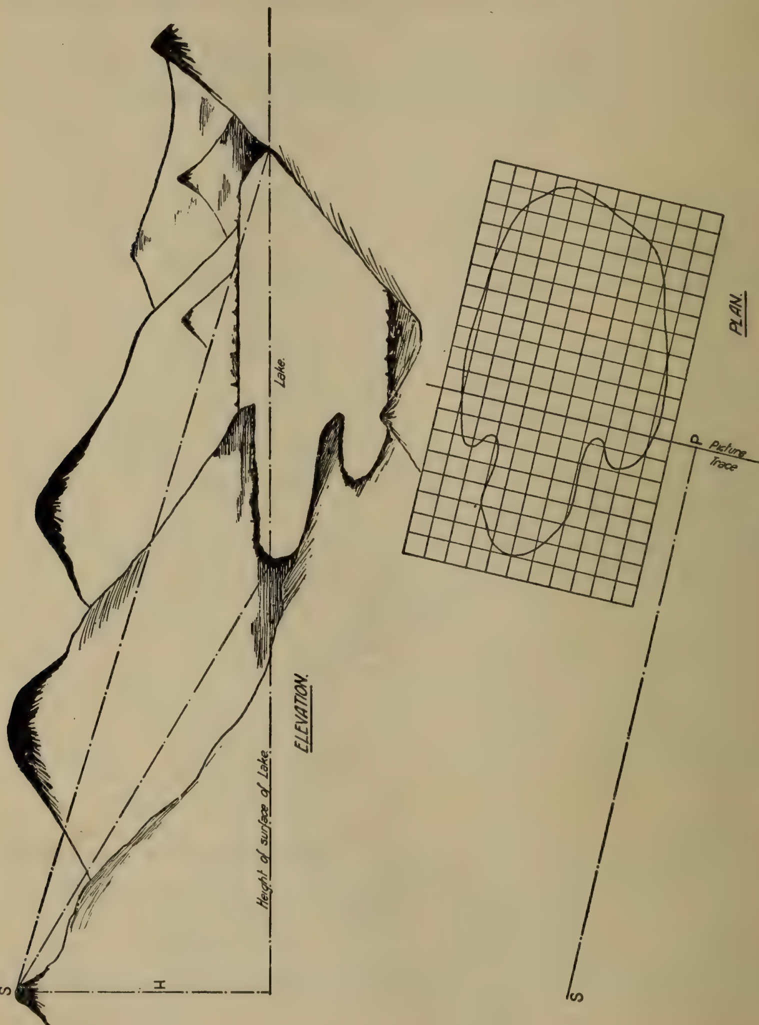

Fig. 11

which may be mapped direct from this one photograph, providing that the camera station is high enough above its surface to give a sufficient vertical base.

Probably the easiest way is to cover the area to be mapped in

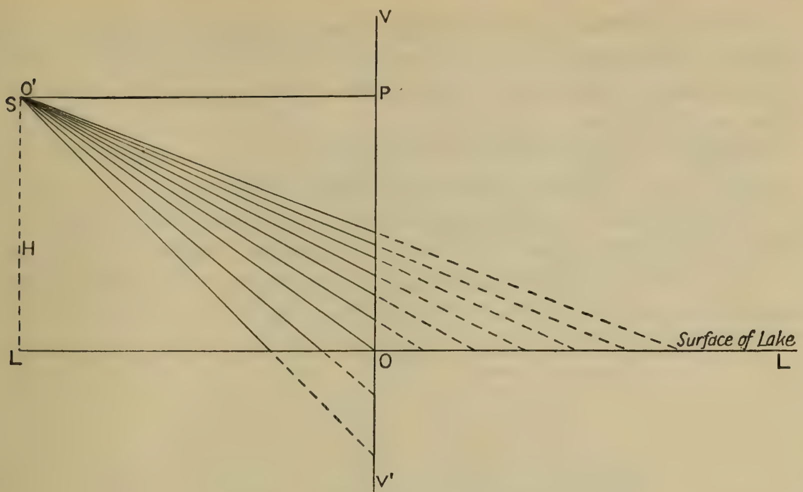

Fig. 12

this way with a grid which is parallel to and perpendicular to the picture trace, and to reconstruct the perspective of this grid upon the photograph

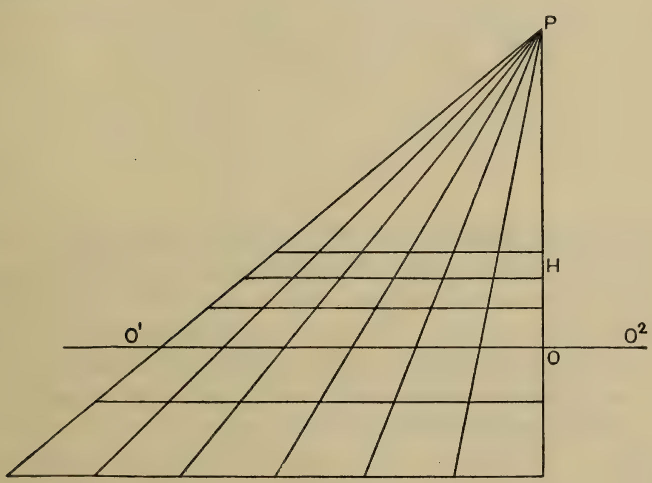

Fig. 13

Draw the principal line (fig. 12) VV′, the optical axis cutting the former in P the principal point, and the plane of the surface of the lake LL parallel to SP at height H below the camera station, and cutting VV′ in O.

On LL dot the points defining those lines of the grid which are parallel to the picture trace. Join them to S, and the points in which they cut the principal line will be points on the perspectives of these lines as plotted on the photograph.

The lines perpendicular to the picture trace, as horizontal and parallel lines, will vanish on the horizon at P (fig. 13).

Now consider the photograph and on it P and $O'O^2$, the trace of the horizontal plane of the lake's surface. On $O'OO^2$ space off the points of the grid at their true intervals. Join these points to P.

Now to OP transfer the distances found on VV′ (fig. 12) for the

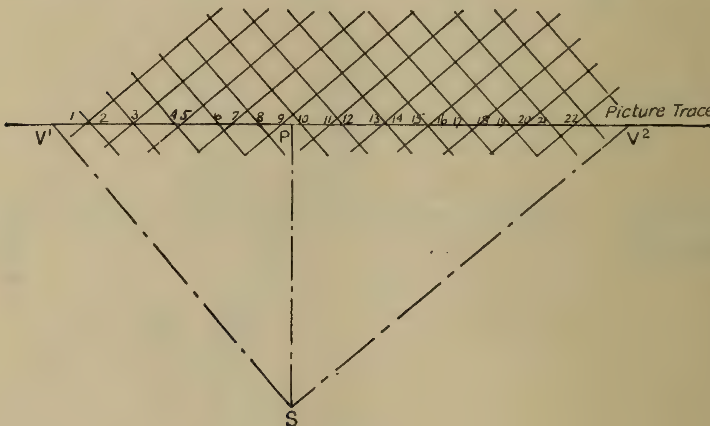

Fig. 14

lines of the grid parallel to $O'O^2$, and draw the parallels through these points. A perspective of the grid on the map is now shown on the photograph, and the map can be completed by eye.

It may occur, however, that the compilation diagram is already covered with a network of squares or " gridded ". Such will usually be the case in military operations, and it is as well in such cases to use the existing grid for perspective drawing.

In fig. 14 a portion of the grid is shown, and the picture trace in its correct position for a station S. The spots at which these grid lines cut the picture trace should be marked on the edge of a slip of paper on which P, v', and v^2 should also appear.

We have now to construct a perspective of this grid on the photograph.

From the horizontal trace (fig. 15) drop a perpendicular from P,

and on it mark S (the station) with SP $= f$. Cutting SP in Q, draw a line $Q'Q^2$ parallel to the horizon trace and at a distance below it equal to the difference of altitude between the camera station and the surface of the lake.

Through S draw lines parallel to the grid lines and at right angles to each other, cutting the picture trace in v' and v^2.

Lay the slip of paper, with the grid cuttings on it, along $Q'Q^2$, so that the position of P on the paper slip coincides with Q; mark on $Q'Q^2$ the grid cuttings and the points v' and v^2.

From v' and v^2 erect perpendiculars, cutting the horizon trace

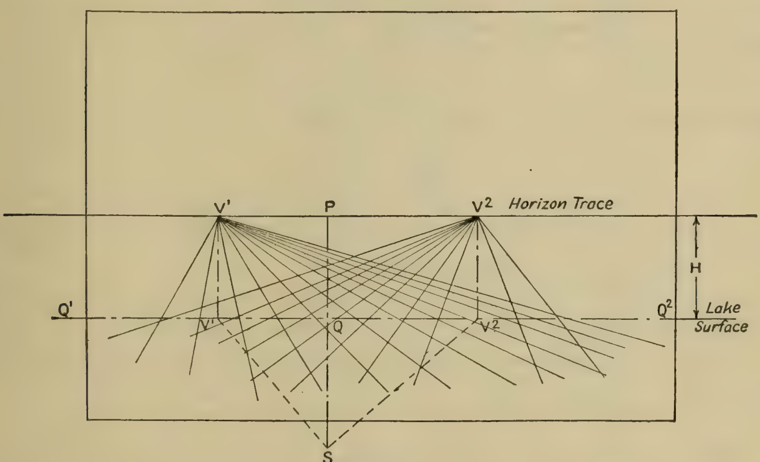

Fig. 15

in V' and V^2. Then V' and V^2 are the vanishing points of the grid lines, and by joining V' and V^2 to the marked points (in this case V' to odd numbers, V^2 to even numbers) the perspective of the grid is shown on the photograph.

In both the foregoing cases of perspective it must be remembered that the scale of the grid or map is the scale at which the difference of altitude must be shown, whilst the focal length is shown, as usual, its true size.

Checking the Interior Adjustments of the Camera.—Providing due care is exercised in the field, the positions of the principal line and the horizon trace should be well established. It is, however, advisable to check the focal length occasionally during plotting, and this can be done if the images of two trig points are visible on the plate.

If we refer to fig. 10 we see that the height of any point A (shown as AA′ on the figure) is computed from the equation

$$AA' = \frac{aa' \times SA'}{Sa'},$$

and

$$Sa' = \frac{aa' \times SA'}{AA'},$$

and

$$Sa' = \frac{SP}{\cos a'SP}$$

$$= \frac{f}{\cos a'SP}.$$

We have then

$$f = \frac{\cos a'SP \times aa' \times SA'}{AA'};$$

but the angle a'SP is defined by its sine,

$$\frac{a'P}{Sa'} \text{ or } \frac{x^a}{Sa'}.$$

If then AA′ or difference in height between the camera station and A be known, we may compute f.

It is wise to confine this computation to occasions where at least two trig points of known height are visible on the plate.

If we set the camera so that the image of A lies on the principal line, then $\cos a'SP$ vanishes and we have $f = \dfrac{aa' \times SA'}{AA'}$.

We may also check the focal length by the method described by Franz Hafferl if two trig points A and B appear on the plate.

Let HH′ (fig. 16) be a picture trace, P the principal point, and let a and b be the points on it defining the abscissæ Pa (or x^a), Pb (or x^b). At S (the position of the camera station) the angle aSb has been observed and equals θ.

Suppose a circle drawn such that it passes through ab and S with centre at O, and from O draw lines Oa, Ob, and OQ perpendicular to ab in Q. Draw SP, Sa, and Sb.

Then $$SP = f = ST + TP.$$

Now $$TP = OQ = \frac{x^a + x^b}{2} \cot aOQ,$$

but $$a\hat{O}Q = \tfrac{1}{2}\, a\hat{O}b = \theta;$$

$$\therefore TP = \frac{x^a + x^b}{2} \cot\theta.$$

Through O draw cd parallel to ab, and cutting SP in T. Now ST is perpendicular to cd, and therefore

$$cT : TS :: TS : Td,$$

$$\begin{aligned} \text{or } TS^2 &= Tc \times Td \\ &= (r + OT)(r - OT) \\ &= (r + QP)(r - QP) \\ &= \left(r + \frac{x^a - x^b}{2}\right)\left(r - \frac{x^a - x^b}{2}\right), \end{aligned}$$

or $$TS = \sqrt{\left(r + \frac{x^a - x^b}{2}\right)\left(r - \frac{x^a - x^b}{2}\right)}.$$

where $$r = \frac{x^a + x^b}{2} \operatorname{cosec}\theta.$$

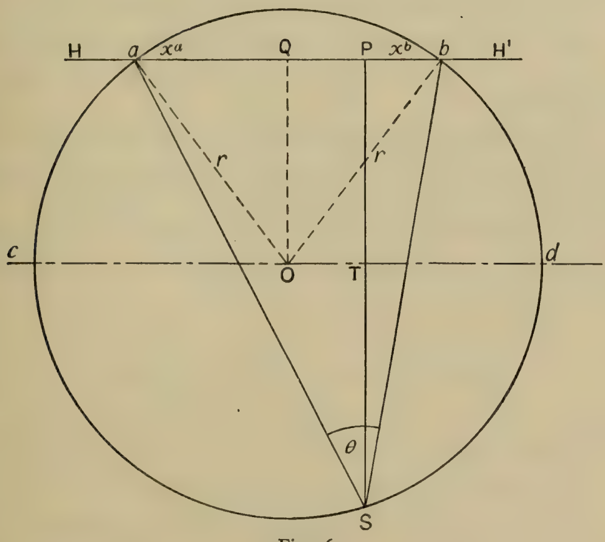

Fig. 16

The Use of this Method.—We will now consider the sphere of usefulness of ground photo-topography and how it compares with other topographical methods.

In the first place it is not a suitable method for either cadastral or very small scale topography. In the former case the size of the scale and the importance of the actual ground plan make it necessary to survey each feature on the spot. Particularly is this so in woody

and enclosed country. In the latter case, so much has to be generalized or omitted that many of the advantages of the photograph disappear, and if photography is used it becomes a question whether the rougher results from the panoramic camera may not suffice. In such cases the cost of the survey is largely due to transport and travelling generally. It is at medium scales and for engineering surveys that its greatest value is to be looked for. The greatest danger is that of leaving gaps uncovered by the photographs, and it is not always economical to take the number of views necessary. For this reason it is economical to be prepared to use other supplementary methods as occasion demands.

As a method, it is quite unsuitable in flat or gently undulating country, and finds its chief justification where the ground to be surveyed is at once mountainous and difficult of access.

It may be said to save time in the field and to add to the office work. The actual detail survey is carried out on perspectives of nature, which are often hard to read, but which on the other hand permit of more prolonged study than can be made of the ground by the plane-tabler.

The results obtained do not check each other during the progress of the work as does plane-tabling, and may show serious errors wherever the position of a point depends upon two rays only.

Lastly, the order of precision of the method is sufficiently expressed by graphic plotting, and there appears no justification for mathematical treatment.

Section IV.—Air Photo-topography

General.—In its earlier stages aerial photography was carried out from balloons or kites, and resulted in little of practical value in spite of the hopes which were entertained.

The rapid development of dirigible aircraft has, however, entirely changed the situation, and the fact that armies in the field were engaged in mapping areas at the moment in the hands of the enemy and therefore inaccessible, added to the importance of this method of topography. At this point it will be as well to draw a sharp distinction between mosaics and maps. The former, a patchwork of vertical photographs, can be made up for small areas but not for large ones, for the difficulties of fitting the photographs together presently become insuperable. They give information of great value, especially in war-time, but are uncertain in scale, rarely escape occa-

sional faults of fit along the margins of adjoining photographs, show neither contours nor names, and, generally, have considerable distortion on the outer edges.

The latter are built up upon a skeleton of fixed points which forbid the accumulation of error and the distortion inherent to the actual photographs. It is with the latter that we are here concerned, and the field work of such surveys has for a start to cover the area to be mapped with a sufficient trigonometrical skeleton. The operations necessary to this end are described in all books on survey and will not be further dealt with here, and the number of fixed points desirable will be considered later. As regards the cameras used for the purpose, the methods of photography, the arrangements for covering a definite area, and the development of prints, see chapter on aeronautical photography. In view, however, of the subsequent discussion on plotting, the following facts must be reiterated.

In the first instance, aerial cameras have hitherto been designed without much reference to the exactness of the interior optical adjustments.

This is due partly to the fact that most British mapping was carried out in areas where old cadastral plans existed, and where precision in the data for rectification was not so important as it will often be, and partly to the necessity of a quick and automatic change of plates which is difficult to combine with the accurate fit of each individual plate.

Secondly, at the moment, there is no method of controlling the camera so as to ensure a constant position of the optical axis relative to the earth, and thirdly there is no precise method of measuring the direction and magnitude of the angle of tilt at the instant of exposure.

When the photographs have been taken and the map compiled, subsequent field work is necessary for naming and, generally, the contouring, whilst it is also advisable to check, on the ground, details —artificial or natural—of topography which cannot be decided definitely from the photographs.

The scope of the field work necessary varies, however, in accordance with the class and scale of the map to be made, and must be referred to later as these points are dealt with.

Tilt of the Photograph.—It has already been mentioned that it is possible from the air to secure a photograph of the area to be surveyed upon a plate parallel to the ground. In such a case the negative is a perfect plan of the detail if the area in question is a

flat plain. Large areas were mapped in the war on this assumption, but investigation proved that practically all photographs were tilted and many by as much as 10°.

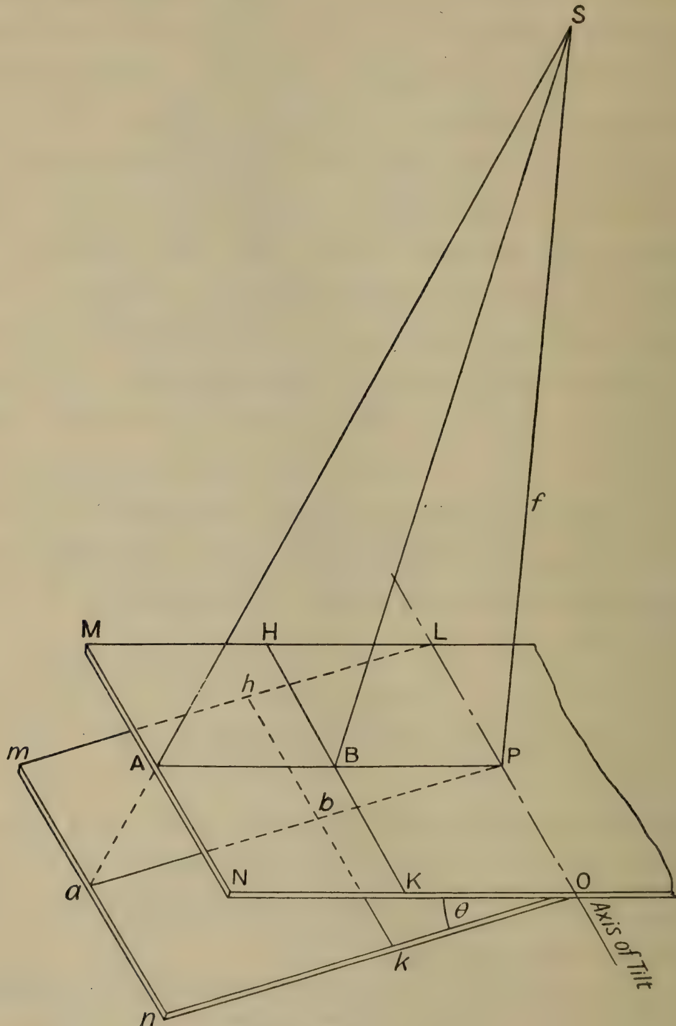

Fig. 17

It was also proved, however, that after careful training pilots could much improve on this figure.

We may take it that the tilt should not exceed 5° generally in

photographs taken for the express purpose of mapping when there is nothing to distract the pilot's attention.

This is an important point, because the greatest value in air photo-topography appears to lie in the survey of plains, river basins, deltas, swamps, coast lines, towns, &c., at medium scales and in conjunction with some other method of topography, such as stereo photogrammetry or plane-tabling, which would complete the hilly areas. In such cases we may consider our only large source of error to be the tilt, and upon the magnitude of the errors we expect from tilt will depend the method of rectification and the number of trig points necessary. It may also be possible to reduce the tilt by some form of mechanical damping.

Let us then consider what linear errors are introduced by tilting the plate.

Let LMNO (fig. 17) be one half of a photographic plate inclined to the horizontal at an angle θ;
- S, station;
- P, principal point;
- PA, trace of the principal plane;
- LO the axis of tilt;
- L*mn*O, a plane representing the map at an angle θ to LMNO.

Now consider the triangles SAP and S*a*P.

Let AP $= x$, *a*P $= y$, the angle at S be ϕ, and the angle at *a* be ψ. Then the angle

$$\text{PA}a = 180 - \text{P}\hat{\text{A}}\text{S}$$
$$= 180 - (90 - \phi)$$
$$= 90^\circ + \phi;$$

but
$$\frac{y}{\sin \text{PA}a} = \frac{x}{\sin\psi},$$

or
$$\frac{y}{\cos\phi} = \frac{x}{\sin\left(\frac{3\pi}{2} - \phi - \theta\right)}.$$

$$\therefore y = \frac{x}{\cos\theta - \tan\phi \sin\theta}$$
$$= \frac{x}{\cos\theta - \frac{x}{f}\sin\theta}.$$

The equation then determines the linear error of scale along MN, and in the distance AP. If we differentiate this equation with respect to x we shall get the actual and local error of scale at any place on the line AP.

Now $$dy = \frac{dx \cos\theta}{\left(\cos\theta - \frac{x}{f}\sin\theta\right)^2}.$$

Let B be such a point that AB = BP. Let us consider $\theta = 5°$, $f = 8$ in., and OL = KH = MN = 7 in. Then we find approximately that error of scale on

MN is 4 per cent, and the error of the length AP is 4 per cent.
HK is 2 per cent, and the error of the length BP is 2 per cent.

The scale errors at different points on PA are:

at P, 0·4 per cent,
B, 4 ,,
A, 8 ,,

We will now consider the effect of small differences of altitude.

Relative Heights.—We have so far considered the surface to be mapped as a plane. If it is not so, differences of altitude will naturally imply errors.

Thus in fig. 18 BC, a tall chimney, appears partly in relief on the plate as ab. In the case of a chimney it would probably be possible to identify b (its foot), but in the case of a hill it would not.

The errors due to heights are shown in fig. 19, for plates taken with an 8-in. focal-length camera.

Referring to fig. 18 it is obvious that

$$AB : AO :: CB : H$$

or $$AB = \frac{AO \times CB}{H}$$
$$= \frac{aP \times cb}{f}.$$

These errors must be taken as emanating from the photo plumb-point, and if we assume a tilt of 5°, this will lie at a distance of 0·7 of an inch (f tan 5°) from the principal point.

Joint Effect.—Naturally the error due to relative heights and to tilt may act in unison. Let us take a case. We will suppose the centre half of each photograph to be used for plotting, arranging for

a half overlap. Let the scale be 1 : 20,000, the focal length 8 in., and the tilt 5°; and let a hill 100 ft. high appear on the edge of the accepted strip (at *b* in fig. 17). The photo plumb-point will be 0·7

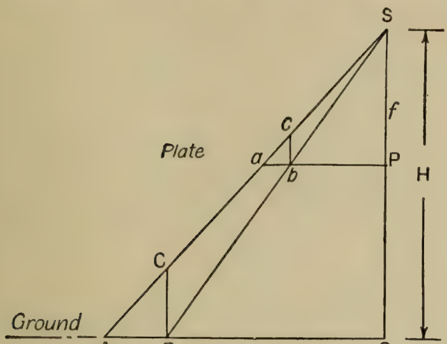

Fig. 18

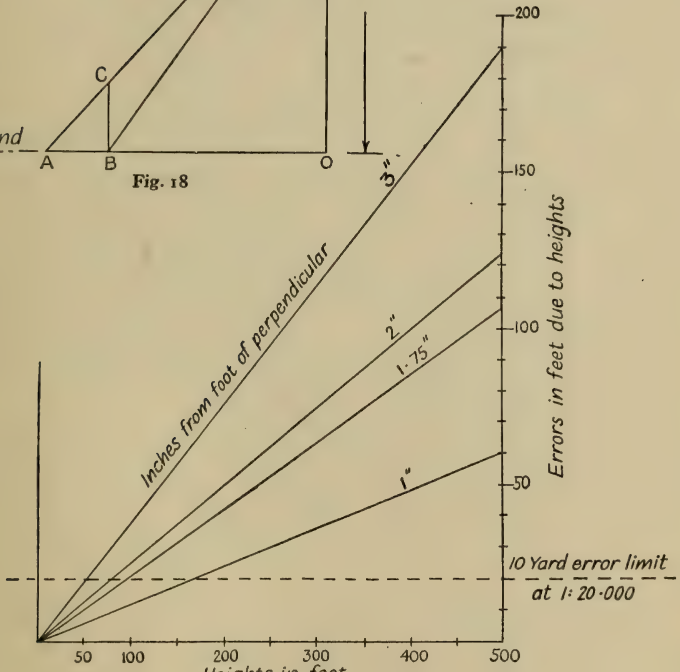

Fig. 19

of an inch on BP produced. Then the total error in the length BP will be as follows:

2 per cent of BP (nominally 972×) ..	19·4 yd.
Error due to height of B (100) at a distance of 1·7 + 0·7, or 2·4 in. ..	10·0 ,,
Percentage error on 10 yd. due to local lengthening of scale at B (4 per cent)	0·4 ,,
Total error	30 yd.

Or 0·05 of an inch.

Vertical Photographs.—The scale of 1 : 20,000 was selected for the foregoing example because it shows the point at which rectification of each photograph should be carried out for accurate mapping. 0·05 of an inch is considerably more than errors of plotting normally produce. If then we want to make accurate surveys at 1 : 20,000 or larger from vertical photographs, each photograph should be rectified. For rough topography it will still be possible to combine say 6 to 12 photographs in a strip, and scale off the strip between trig points, equating small divergences between strips in their overlap, and this procedure will probably suffice in all cases for surveys of flat areas on scales smaller than 1 : 20,000. The procedure in such cases will be as follows.

The trigonometrical skeleton will provide points at from 5 to 10 miles apart, and the aeroplane will fly as direct as possible between points, photographing the sides of the triangles. These photo sides will be mounted and reduced or enlarged to the correct lengths. Finally the whole area will be photographed in parallel strips, fitting on the trig points and the photographed triangle sides.

In this way the areas difficult of access for survey on the ground, or unsuitable for ground or stereo photo-topography, may be filled in, and during a subsequent examination on the ground, names will be added and doubtful points cleared up.

The obvious danger of these photo traverses, as they may be called, is that the height of the aeroplane may vary. Small deviations above and below the general line of flight may be kept within something of the order of 100 ft. under good conditions, but experience has shown that there is a tendency for a gradual and continuous rise or fall.

Tilt Measurement.—At the moment there are no precise means of measuring the tilt at the instant of exposure. It must follow in the office, therefore, and can be done in three ways—mathematical, geometrical, and optical.

Mathematical.—Let S, fig. 20, be the position of exposure in space; RSTU the plane of the survey; *rstu* the plane of the photograph. (This plane actually falls in a similar position on the other side of S, but it is more convenient and equally precise to place it below S.)

Let P be the principal point; SP $= f$ the focal length; V and V′ be the map and photo plumb-points; and let A, B, C, and E be four trig points on RSTU, with images a, b, c, and e on the photograph.

Then PV′ (= d) shows the direction of tilt and its magnitude. Thus, if θ be the angle of tilt, $\theta = \tan^{-1}\frac{d}{f}$,

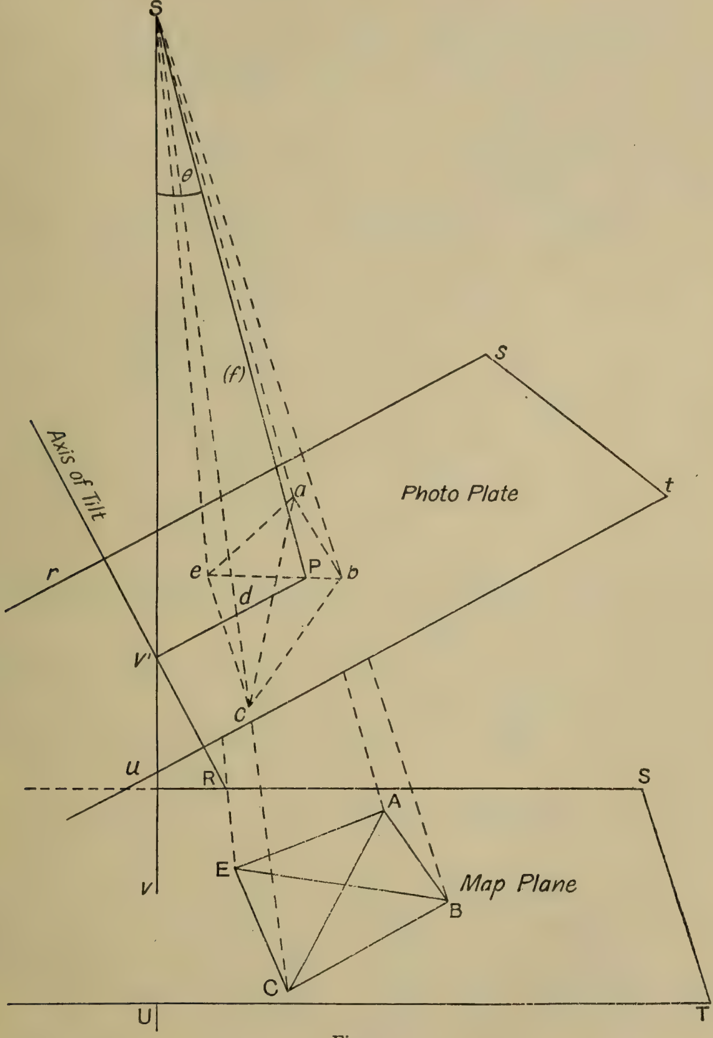

Fig. 20

Generally speaking three trig points common to both planes will suffice for a solution, but there is occasionally an alternative case, and four points ensure a correct result.[1]

[1] M'Leod, *Mapping from Airphotographs.*

Treated mathematically we see from fig. 20 that the angles subtended at S by the lines joining any two points are the same in pyramids *abce*S and ABCES. The co-ordinates of *abce* are measured on the plate with reference to P, and SP being known the angles *a*S*b*, *b*S*c*, &c., are calculated. We have now constructed the apex of the pyramid ABCES, and there is only one position in which ABCE will fit in that pyramid.

This position, computed by successive approximations, fixes the co-ordinates of S in space.

Within the limits of this chapter, it is not feasible to go further into the question. Computations are long and cumbersome, and

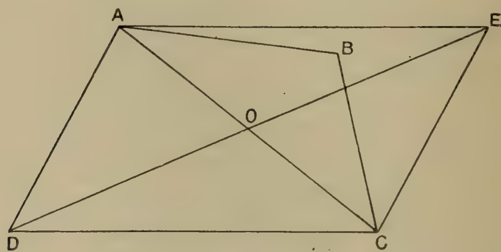

Fig. 21

at present hardly justify the time involved. The subject may be studied further in the following books:

Grundlagen der Photogrammetrie aus Luftfahrzeugen, by Hugershoff and Cranz (Stuttgart, 1919).

Ueber Photogrammetrie aus Luftfahrzeugen, by Professor Pulfrich (Jena, 1919).

Ueber die Berechnung des räumlichen Rückwärtseinschnitts bei aufnahmen aus Luftfahrzeugen, by Dr. Aug. Fischer (Jena, 1921).

Geometrical.—There are several geometrical methods of determining the direction and magnitude of tilt,[1] but, in the writer's opinion, the following, described in *Applications de la Photographie Aérienne* (Clerc) and in manuscript by Major King, O.B.E., R.E., and G. T. M'Caw, Esq., is the most effective.

Let ABCD, fig. 21, be any four trig points on the map whose images are *abcd* on the photograph.

On any two sides, AD and DC, construct a parallelogram AECD,

[1] *Mapping from Airphotographs*, Lt.-Col. M'Leod, D.S.O., R.E.; *Applications de la Photographie Aérienne*, Clerc.

and transfer (by the four-point method, see p. 352) E to the photograph in *e*. Join AC and DE, cutting in O, *ac* and *de* cutting in *o*.

Let P (fig. 22) be the principal point.

Now if we produce the opposite sides of the quadrilateral *aecd* to meet in *j* and *k*, we shall form a " complete quadrilateral ", the third diagonal of which (*jk*) is a horizontal line. That this is the case may be shown briefly as follows.

It is a perspective law that the third diagonal of any quadrilateral must coincide with the third diagonal of any perspective of that quadrilateral. But the third diagonal of a parallelogram is at infinity, and therefore the plane including its perspective and that of the perspective centre (lens) must meet the plane of origin in infinity, and must therefore be parallel to it.

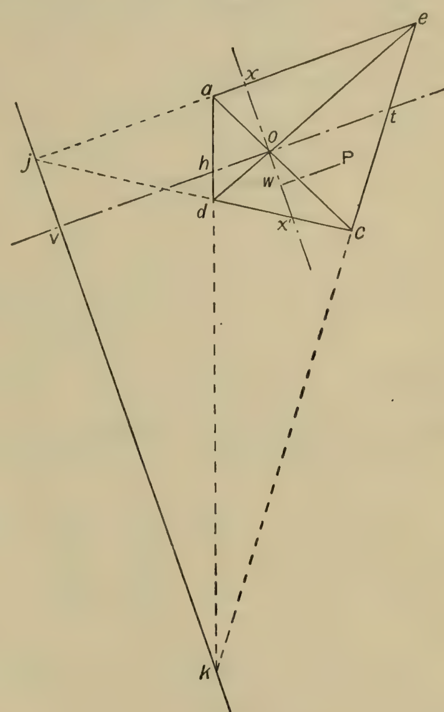

Fig. 22

Now it is not usually convenient to find the points *j* and *k* graphically, for with small angles of tilt they lie too far and are fixed by angles of intersection too acute. It is best then to construct through *o* a line parallel to *jk*, and to calculate the perpendicular distance from *o* to *jk*. By trial and error find a line passing through *o* and cutting any two sides of the quadrilateral in x and x', so that $ox = ox'$. Then xx' is parallel to *jk*. This follows, because any line drawn from one side of a parallelogram to the opposite side through the crossing of the diagonals is bisected at that point. Any line on the perspective which has the same property is therefore in a plane parallel to that of the parallelogram and to the perspective of the third diagonal.

Draw P*w* perpendicular to xx' in *w*.

In fig. 23 V is a point on the line *jk*, such that PV is perpendicular to *jk*; S is the perspective centre, and SV is horizontal; P is the principal point. Then PVS $= \theta =$ the angle of tilt, and can be defined as $\tan^{-1}\frac{f}{\mathrm{PV}}$.

Now refer to fig. 22. Draw *toh*V perpendicular to *xx′*, and cutting

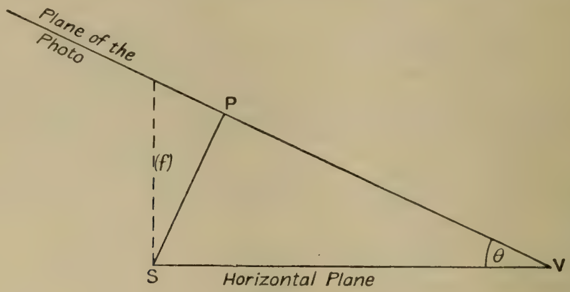

Fig. 23

two sides of the quadrilateral *aecd* in *t* and *h*, *xx′* in *o* (the intersection of the interior diagonals), *jk* in V.

From the harmonic proportions of the complete quadrilateral

$$\frac{to}{oh} = \frac{t\mathrm{V}}{h\mathrm{V}} \text{ or } \frac{to}{oh} = \frac{o\mathrm{V} + to}{o\mathrm{V} - oh}.$$

$$\therefore\ o\mathrm{V} = \frac{2\,to - oh}{to - oh}.$$

Measure the lengths *to* and *oh* and compute the length *o*V. Add to *o*V the length P*w*, and the result (*o*V + P*w*) is the length shown as PV in fig. 23, and $\frac{f}{\mathrm{PV}} = \tan\theta$.

Optical.—Optical methods can be devised by exactly reproducing the interior adjustments of the camera and by fitting the photographic image upon the map.

Thus, if we look at fig. 20 and consider S to be a pinhole through which we may regard the map and photo planes, and if we represent by a sheet of glass, upon which are plotted the trig points, that plane which comes nearest the pinhole, we can, by trial and error, find the right relative positions of the two planes.

To reproduce the exact conditions of exposure, PS must equal the focal length, and allowance must be made for refraction in the glass plate.

The primary value of this adjustment is of course to find V′ (fig. 20), and by joining it to P to measure the direction and magnitude of tilt.

An instrument is already in existence for this purpose, although it has not been placed on the market.

Of these methods the mathematical and optical can be made to allow for relative differences of altitude of the trig points. Successive approximations have to be made in each case, however, as the position of the photo plumb-point must be determined approximately before the direction of the corrections for altitude can be applied. The photo plumb-point has then to be redetermined, which in turn gives a second approximation for the direction of the corrections for altitude.

The geometrical method cannot be used readily in this way, and should be confined to trig points which lie at about the same altitude.

Rectification.—Rectification is the process of projecting a tilted perspective image back into the horizontal plane.

The steps taken depend, however, on how far we shall make use of the rectified image.

If air photo-topography is used merely for additions or corrections to a map, simple methods will suffice.

If the whole of the image is to be used as the only method of detail survey, it is advisable to rephotograph the tilted plate so as to bring the whole into the horizontal plane. All methods of rectification assume the earth to be flat, but an allowance can be made for the height of the controlling points, above or below the plane of reference, either mathematically or mechanically.

The simplest method, an effective one in many instances, is to follow perspective law No. 1 (p. 352), and to fix any point on the map by the intersection of lines joining already plotted detail points.

Thus, if a new house to be placed on the map is found to lie in the photograph on such an intersection as is shown in fig. 24, the same intersection will define its position on the map.

If sufficient points are not available, a few more may be transferred from the photo to the map by following the second perspective law (the four-point method).

Within narrow limits the proportional compass may be used, but it must be remembered that local variations of scale on a tilted plate are not of the same order perpendicular to and parallel to the axis of tilt, and that no reliance must be placed upon points so fixed.

Perspective grids may be readily constructed from five or more

points common to map and photograph, and if four points are actually common, a fifth can be added by the four-point method.

Thus ABCDE and *abcde* (fig. 25) are points common to map and photograph, and by joining each point to all others a network is established which fixes other points such as, for example, 1, 2, and 3 on the map, whose images are ①, ②, and ③ on the photograph. By con-

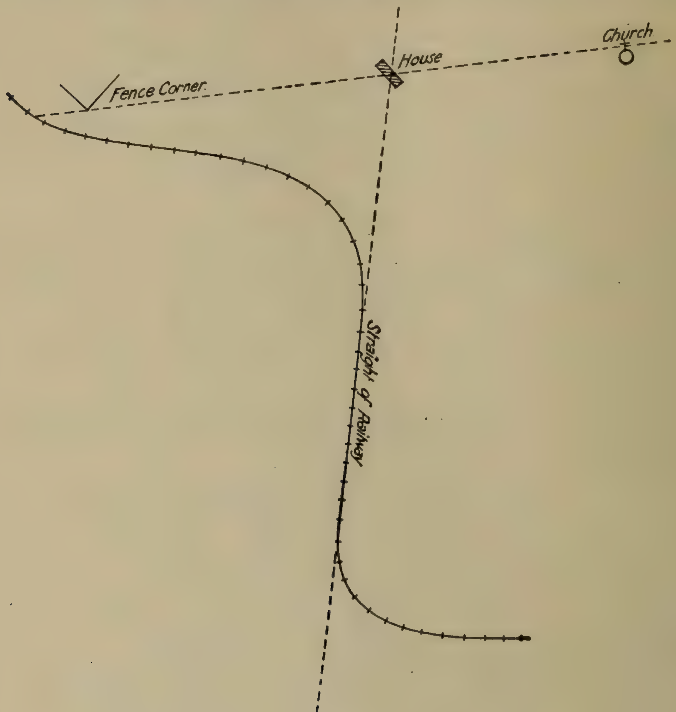

Fig. 24

tinuing to join up points of intersection the grid may be made as close as is desired, and detail may be drawn in on the map by eye.

It follows that if one desires to make on the photograph a perspective of a grid on the map, it is necessary only to establish corner points, and two or three others by the four-point method on the photograph, and to complete by joining points of intersection.

The camera lucida is an instrument which, by the aid of a prism, enables one to superimpose one image upon another. In this particular case it throws the image of the photograph on to a tracing of the fixed points which is pinned on the copy board.

Various designs of camera lucida have already been used in air phototo-pography, but few have maintained the rigidity absolutely essential to a survey instrument.

In the earlier patterns, copy board, photograph board, and prism were all movable in every way and in every direction, and the bewildering effect of these movements, combined with the instability of the instrument itself, made it at once tedious and inaccurate to use.

Fig. 26 shows a pattern which combines simplicity and rigidity, and the movements are confined to those which are essential, and which are in conformity with perspective laws 3 and 4 (p. 353).

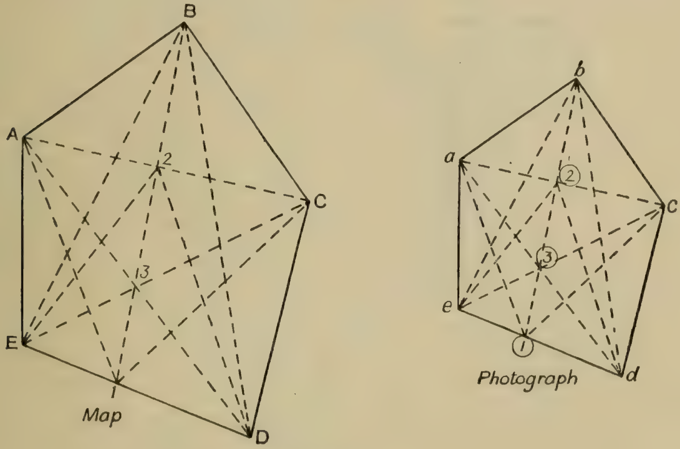

Fig. 25

The camera lucida fulfils, however, a position intermediate between the graphic methods (given above) and the photographic method (which follows), and is not a particularly valuable instrument.

Photographic rectification is undoubtedly the most effective method of recovering a parallel perspective where almost all the detail is to be taken from the photograph.

In the first instance we have to follow the same laws of perspective as before.

As an instance of this fact, suppose the horizon trace appears on the plate. This trace must obviously be projected into infinity in rectification, or, in other words, the rays passing through the lens from this horizon trace must be parallel to the copy board.

The relative positions of planes and perspective centre (or lens)

would in fact follow from perspective laws 3 and 4, amplified by the scale factor (or the height of the aeroplane), if we were not also bound to ensure a sharp focus over the rectified print.

Supposing that we place the photograph to be rectified at a distance from the lens of the enlarging camera equal to the focal length

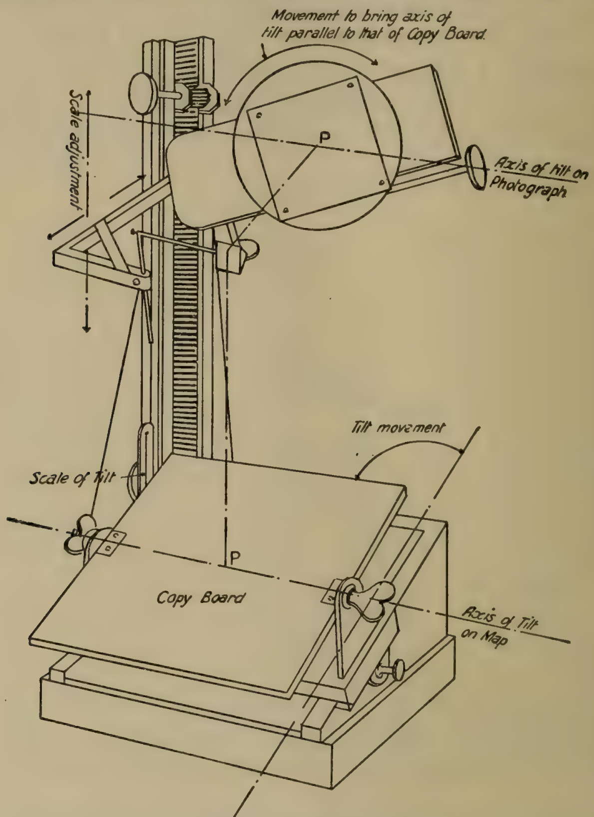

Fig. 26

of the surveying camera, then the focal length of the former should be a function of the latter and of the height of exposure, which implies a constant change of lens. This is impracticable, and we have therefore to find with one lens positions for both plate and copy board which will satisfy the demands of perspective and focus for various cases.

In the first instance the plate-carrier and the copy board must hinge on horizontal lines (or at any rate on parallel lines)

which represent the axis of tilt.

The angles at which they are hinged are governed by the focal lengths of enlarging and surveying cameras, the angle of tilt, and the scale factor; their respective distances from the perspective centre by the angles at which they are set; and the focal length of the enlarging camera and the two planes AB and *ab* (fig. 27)—perspective and rectified—to be conjugate must intersect each other in the plane of the lens.

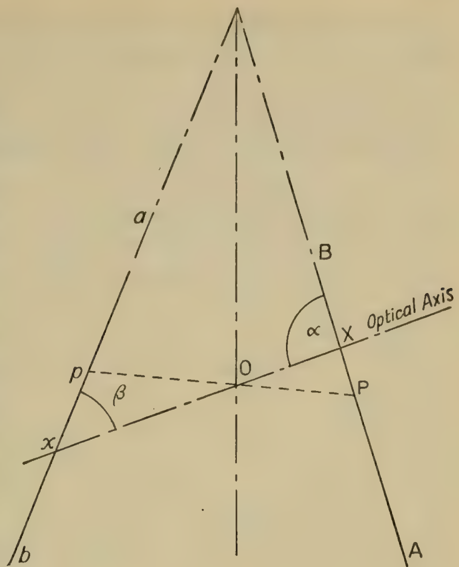

Fig. 27

In fig. 27, let f be the focal length of the surveying camera,
f', the focal length of the enlarging camera,
m, the scale of the map,
θ, the angle of tilt,
H, the height of the aeroplane at the instant of exposure,
O, the perspective centre,
P, the principal point,
$XP = r$,
$XO = s$,
$xO = t$.

Then $$\cos\alpha = \frac{f'}{Hm}\sin\theta.$$

$$\cos\beta = \frac{f'}{f}\sin\theta.$$

$$s = f'\left(1 + \frac{\tan\beta}{\tan\alpha}\right).$$

$$t = f'\left(1 + \frac{\tan\alpha}{\tan\beta}\right).$$

$$r = f\operatorname{cosec}\theta(\sin\beta\operatorname{cosec}\alpha - \cos\theta).$$

These equations are taken from Colonel M'Leod's book on *Mapping from Airphotographs*, in which the subject is fully discussed, and students are recommended also to study *Applications de la Photographie Aérienne*, by L. P. Clerc, and *Applications de la Photographie Aérienne aux levées topographiques*, by M. H. Roussilhe.

These equations are simple to solve, but imply a knowledge of the magnitude and direction of tilt (the latter in order to place the plate in its true position for tilting). It is possible to complete the rectification by trial and error, but it is much more accurate and economical of time to find the tilt previously by one of the methods already given.

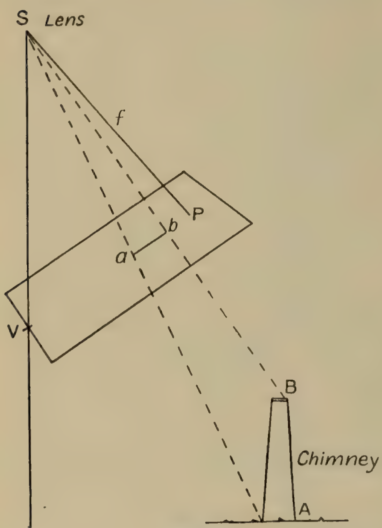

Fig. 28

Practically any enlarging camera will serve, but it must possess the following movements.

The plate-carrier must have a rotary movement round its own centre in order to set the horizontal line through P horizontal in the camera.

It must also move up and down in order to set P at the correct distance r. It must hinge about the horizontal line (to secure α), and must be movable to or from the perspective centre to secure the correct length s.

The copy board must be tiltable round a horizontal line, and be movable towards and from the perspective centre (to secure β and t).

All these movements must be measurable against scales.

Oblique Photographs.—So far we have discussed vertical photographs burdened with an accidental tilt. It may presently be possible to use such photographs stereoscopically, and to measure relative heights. At the moment, however, it seems more feasible to use oblique photographs for contouring and in much the same way as in ground photo-topography by intersecting each point from two camera stations, and then, by a graphic solution, finding heights.

Now consider an oblique photograph, and on it a small line *ab* which is the image of a chimney (fig. 28). The line *ab* if produced in the direction *ba*, will cut the vertical from the lens in V. For the

map it is the position *a* which is wanted, and we can probably identify *a* in the case of a chimney. We cannot, however, in the case of a mountain or of any "up station" or object whose base is not clearly visible. We must then use the ray V*ab* on the map as a bearing, and get another bearing which will intersect the first in *a* from some other photograph.

Now consider fig. 29. A is the position on the map of the

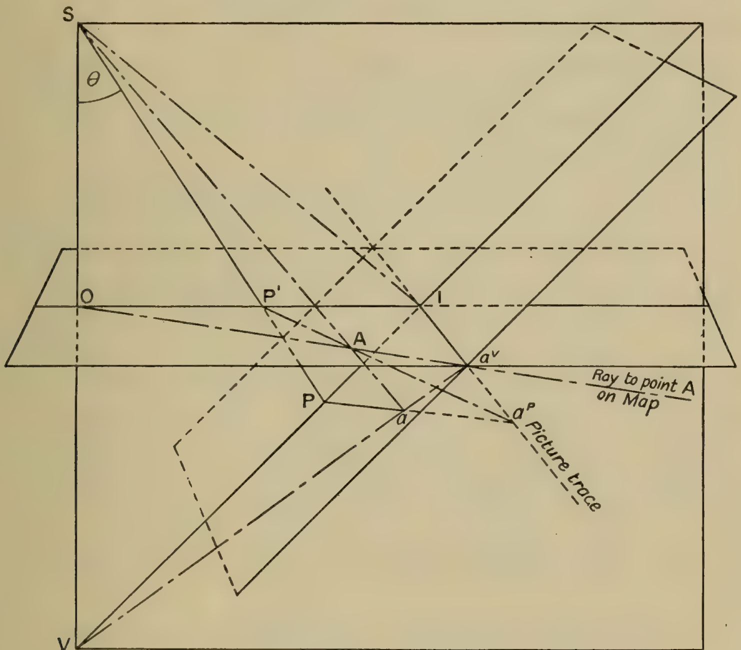

Fig. 29

point *a* visible on the photograph. As *a* may be of any (unknown) height we must fix it by intersection.

We want therefore to plot the ray OA on the map.

> S is the lens;
> O, the map plumb-point;
> V, the photo plumb-point;
> P, the principal point;
> P′, the position on the map plane corresponding to P.

As the photo is inclined to the vertical (by angle θ) the map

plane and photo plane will cut each other (in a horizontal line, since the map plane is horizontal).

Join aV and produce to cut the intersection of the planes in a^v. Then Oa^v is the desired ray on the map plane. For whatever may be the height of A, the ray Va^v (passing through a) includes the horizontal projection of A, and Oa^v is the perspective of Va^v on the map plane.

Now it may be useful to find an approximate position for A by neglecting its height.

If P′ is determined on the map plane, we can find it by drawing on the map plane from P′ the line P′a^p, which is the perspective of a line drawn on the photo plane from P through a, to cut the intersection of the planes in aP.

The line P′a^p will cut Oa^v in A, which would be the true position of a on the map plane if A were a point with no height above or below the plane of reference. If A has any height above or below, its horizontal position must be fixed from two photographs.

Consider the triangle SOA. This triangle has a right angle at O. We will suppose now that by intersection of the ray Oa^v with some other ray the true position of A is found to be nearer to O than A, and suppose that from this true position we erect a perpendicular to the map plane cutting OA. Then the length of this perpendicular intercepted between OA and SA will represent the height of A *above* the plane. Had the true position of A fallen on Oa farther from O than A, then A would have been below the level of the plane, and a similar construction would have shown by how much.

Now turn to fig. 30 in order to see how to make use of these facts. We will suppose the photograph to be stuck down on a large sheet of paper. We have previously determined the magnitude and direction of tilt, and we can plot the principal point and the horizontal line and trace of the principal plane through it.

In the first place we want to plot on the trace of the principal plane the positions of O and V, and parallel to the horizontal line the intersection of map and photo planes.

Along the horizontal line set off PS $= f$. From S, draw SV at angle $= \theta$ to cut the principal plane line in V.

Then PSV is the same triangle as that in fig. 29.

Make SO equal to the height of the lens above the map plane (as in fig. 29).

At O set up a perpendicular to SV, cutting VP in I and PS in

P′. With centre I and radii IP′ and IO, describe arcs of circles cutting IV in (P′) and (O). Then (P′) and (O) are the positions on the trace of the principal plane of P′ and O, and this will be clear from comparison with fig. 29.

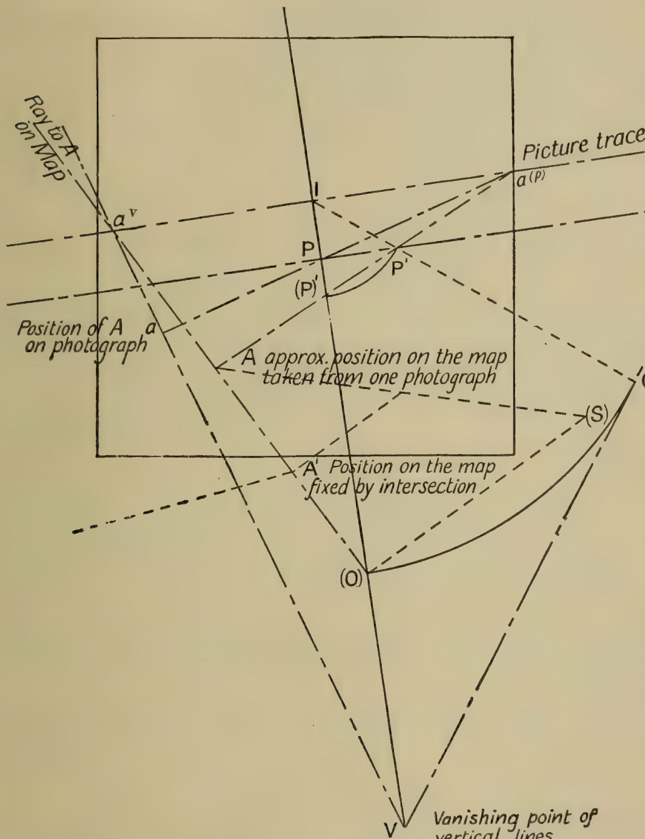

Fig. 30

Through I draw a line parallel to PS. This line is called the picture trace.

Now to plot upon the map, we will make use of the point (O) and the picture trace.

Transfer (O) and the picture trace to the map. We now require the points on the picture trace through which to draw rays.

Take any point *a* on the photo (fig. 30).

Join *a*V and produce backwards to cut the picture trace in a^v.

With a slip of paper transfer the position of a^v to the picture trace on the map. Draw $(O)a^v$, and on this ray will be the position of A.

To find an approximate position join aP to cut the picture trace in a^p. Join a^pP′, cutting $(O)a^v$ in A.

Then A is the approximate position.

Now we will suppose that from some other inclined photograph another ray is drawn cutting $(O)a^v$ in A′, and establishing A′ as the true position of a on the map. What is the height of A′?

On the line $(O)a^v$ construct the triangle (O)(S)A corresponding to the triangle SOA in fig. 29.

From A erect a perpendicular to (O)A′ intercepting a distance h. Then h is the height of A′ above the plane of reference.

In making these plottings it is desirable to check the orientation of (O)(P′) on the map. The easiest way to do so is to see that rays from (O) passing through any one or more trig points (already plotted) which may be visible on the photo, do actually pass through these points. As a further step it is obvious that the position of (O) can be verified by making a tracing-paper interpolation from any three or more trig points, if so many are common to the map and the photograph.

This same problem may be solved mathematically. It has been so treated in recent German surveys, and the methods may be studied in *Photogrammetrie aus Luftfahrzeugen* (Hugershoff and Cranz).

It is, however, doubtful whether the instruments at present on the market will guarantee an order of accuracy to warrant so cumbersome a solution.

Summary.—The stereoscopic use of air photographs will be discussed later, and we can sum up the sphere of air photo-topography in its present stage of development as follows:

A triangulation, the inevitable preliminary, must include fixed points at every five miles or so for work on small scales in flat country. For accurate mapping, points at every two miles or so will suffice, but should be amplified by others plotted graphically from oblique photographs, from which the contouring will also be done. The detail survey will be plotted from photographically rectified vertical photographs in flat country, and plotted by the picture-trace method from obliques in hilly country.

The ground must then be visited, named, and examined. Such a survey is feasible, but it is doubtful whether it will ever be economical to confine any large survey to air photo-topography.

It is obvious to anyone acquainted with survey methods generally that, at the present moment, air photo-topography of an accurate nature is burdened with an almost prohibitive amount of office work.

This trouble may be largely removed by the precise determination of tilt at the moment of exposure, but the ultimate goal must be the elimination, not the rectification, of tilt, which implies also in the case of obliques the power to photograph at any desired angle.

It would be equally uneconomical, however, to neglect to use it in those cases already alluded to as the most suitable for its employment.

Section V.—Stereophoto Methods

Stereo Photogrammetry.—The eye-base and the convergency from the ends of it (or parallactic angle) give the human being his power of measuring distance, though various other factors, such as colour, the known size of different objects, shadow, &c., help him to his final estimation.

The limit of the power of the human eye to separate one object from another is usually taken as half of a minute of arc. In certain cases it may be more, in others less.

Stereo photogrammetry aims not at measuring range and bearing on the ground, but on two photographs taken of the same landscape at the ends of a measured base. In fact, a stereoscopic effect is only possible when examining two views taken from different places. If we examine two identical copies of a map through a stereoscope, the eyes are not forced to form a parallactic angle, and no sensation of relief can be obtained. The rays from the eyes are, in fact, parallel.

If we regard two negatives N and N′ taken from the ends of a base, placing our eyes at the correct focal length from them, the rays from the eyes through the images a and a' are forced to converge and to give the required effect of a point A.

Fig. 31 shows the general arrangement, and it will be seen that the parallactic angle is equal to $\theta - \theta'$ (having regard to signs), or $\tan^{-1}\frac{x}{f} - \tan^{-1}\frac{x'}{f'}$, and if $f = f'$ can be measured directly as $x - x'$.

The Comparator.—The instruments in which the photographic plates are placed for investigation are known as stereo

comparators. Zeiss & Co., of Jena, have a practical monopoly of these comparators, designed by Professor Pulfrich.

The principle of their construction is as follows (fig. 32).

N and N′ are the two negatives taken from the ends of a base. P and P′ are their respective principal points. P and P′, when the plates are inserted, are the origins of perpendicular rays which pass through a reflecting stereoscopic system which bends these rays inwards at q and q', and then outwards again at r and r' to the eye, enlarging either three or six times in the process.

Now the image is reversed during magnification, and therefore

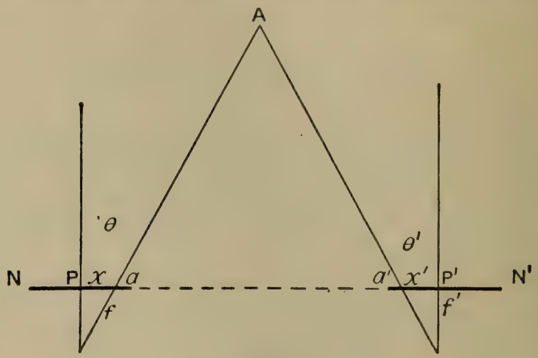

Fig. 31

each ray has to pass through a prism arrangement to reverse this image again.

Finally, in the eye-pieces, two small glass plates, scored with similar vertical marks, provide the " marker ".

This marker is seen by the observer in the landscape as shown by the negatives, and it is by its help that ranges are measured. The plates are subject to certain movements, the amounts of which are read off on scales.

m' (at P and P′) is a rotary movement of the plates round the principal points in order to set the principal lines and horizon traces to the correct marks. m^2 is a lateral movement of both plates at once to the right or left. The left eye (or left end of the base) is taken as the origin from which positions are defined, and therefore the image on N of any point whose position is to be fixed is set by this movement opposite the ray from the left eye-piece (and N′ follows by a like amount). m^3 is a lateral movement peculiar to N′ only, and by its aid the parallactic angle is given and measured.

There are two further movements to be considered which are

not shown on fig. 32. One (common to N and N′) raises or lowers them in their own plane, and the other moves the marker in the eye-piece. This last-mentioned movement serves only to place the marker at an apparent distance in the landscape, which is read off on its scale.

The procedure of measurement is as follows: the image of the point to be fixed on N is brought into the optical axis of the left

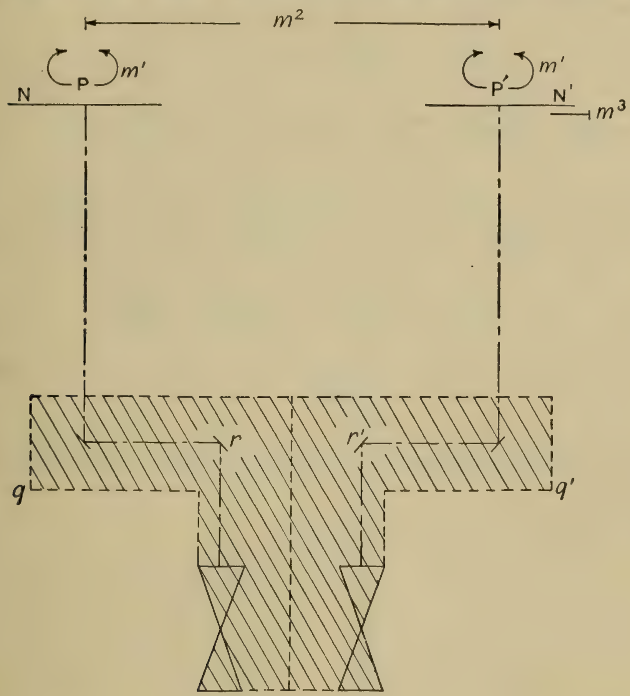

Fig. 32

microscope. Then the movement m^3 alters the parallactic angle and, in effect, moves the landscape towards or away from the observer, whilst the marker remains stationary, although curiously enough it is the marker which appears to move forwards and backwards in a stationary field of view. The amount of the movement of m^2 and m^3 and the position of the marker as previously set, are the data from which the position of the point in question is fixed. Heights are measured directly from the movement of N and N′ upwards or downwards in their own plane in order to coincide with the optical axis of the microscope.

Naturally the actual relative positions used in the field are maintained in the comparator, and fig. 33 shows them in diagrammatic fashion.

O is the point to be fixed, C and C′ the positions of the camera at either end of base L. o' is the image of O on the left negative (N), o^2 the image of O on N′.

Then $o'C = f$ (the focal length of C). $COC' = \theta =$ the parallactic angle $= o^2C'Q$.

Then $D = L\cot\theta = L\frac{f}{l}$.

Then $D = \frac{Lf}{l}$ where L and f are constants and l is measured.

From this formula, by differentiating, we see the influence of errors in the length of the base, and of the distance of the point, for

$$dD = \frac{Lf}{l^2}dL. \quad \text{Now } l = \frac{Lf}{D};$$

$$\therefore dD = \frac{D^2}{Lf}dL,$$

and therefore the error in the distance increases as the square of the distance.

Now if L be regarded as variable,

$$dD = \frac{f}{l}dL.$$

$$\therefore dD = \frac{D}{L}dL,$$

$$\text{or } \frac{dD}{D} = \frac{dL}{L},$$

from which we see that the error in the distance is proportional to the length of the base.

It is claimed for these comparators that the distance l, defining the parallactic angle, can be measured to within 0·01 mm., but the total error in distance will be made up of the error of this measurement and of the measurements in the field.

Stereo Photo-topography Field Work.—The instruments for the field work consist of one or two phototheodolites (or surveying cameras and separate theodolites) and stores for measuring the base.

For convenience the plates are generally exposed in the same plane. In the latest models of comparators allowance has been made for measurement on inclined plates, but in such cases the inclination must be carefully measured in the field.

The length of the base to be used depends, as we have seen, on the distance to which the survey from those particular plates is to extend. The measurement of the base is usually done optically on the tachymeter principle by the special phototheodolites supplied by Zeiss & Co., and up to a length of 200 m. an accuracy of 1 : 1000 is looked for. This implies very careful work. When the base has been measured the phototheodolites are carefully aligned and the exposures are made. Any difference in the altitude of the camera stations must be measured.

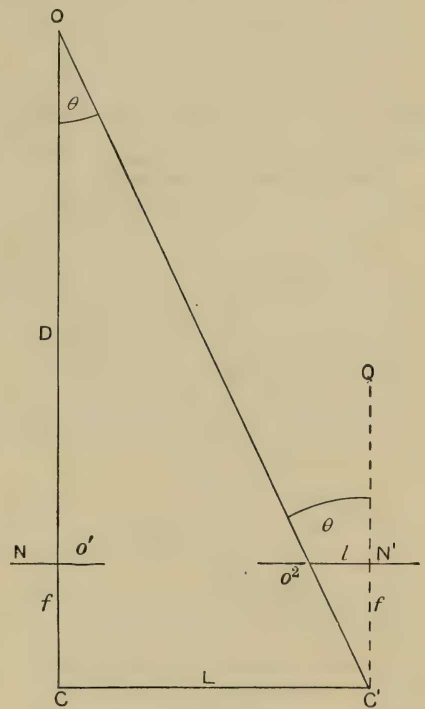

Fig. 33

The left station (looking towards the direction of survey) is taken as the origin for measurement on the plates, and the position of this point must therefore be fixed trigonometrically, but will usually follow by interpolation from bearings observed with the phototheodolite, whilst in position, upon three or more trig points.

Office Work.—The theory of the office work has fallen naturally into the description of the stereo comparator. There are several practical points of interest which remain, however.

In the first instance it must be noted that there is no bother here in the identification of points, and the real difficulties which arise in ground photo-topography from this cause are eliminated.

In the survey of both details and contour, there is available a greatly exaggerated model of the actual ground. In spite of the

claims advanced in favour of ground photo-topography, it remains a fact that the data for contouring leaves much to the imagination. In stereo photo-topography this is not the case, and it is possible by its means to contour flatish areas.

There remain two factors on the reverse of the picture. In the first place, as with every photographic method, it is difficult to cover the whole area, and one is left uncertain as to how much has been missed until the plotting is done.

In the second place each point must be plotted in turn (taking some 5 or 6 min. apiece), and unless this is carried out by different observers at different times mistakes are bound to creep in.

The Stereo Autograph.—A notable stride in the development of stereo photo-topography is the invention of the stereo autograph by Captain von Orel of the Austrian Army.

It is not possible here to attempt a detailed description of this instrument. It can best be compared to a pantograph, if one can be imagined, which can trace horizontal detail and fix relative heights in one and the same operation. It is used in conjunction with the stereo comparator, and, carrying the adjusting movements of that instrument through a system of interdependent parts, plots mechanically and directly upon the map.

Contours, watercourses, railways, and, in fact, any detail may be followed directly, whether in one plane or not. On the one hand, it reduces the time of plotting to about one-sixth, and on the other it eliminates mistakes of calculation.

The Value and Accuracy of the Method.—Stereo photo-topography is the most advanced of the photographic methods of survey. Its accuracy, which may be taken as of the order of 1 : 1000, hardly expresses its advantages.

It must, like all other methods, be controlled by a triangulation, but in accuracy of detail and faithfulness of representation it may be said to be the most promising of all methods.

The drawbacks are the cost of the instruments, the necessity for base measurement (not always an easy operation in mountainous country), and the weight to be transported. Many of its advantages would fail in very large or comparatively small scale work.

In the former case ground plans (and therefore exact areas) would often not be measurable. In the latter, much of the valuable detail would necessarily have to be generalized. It is probable that, like other photographic methods, its chief usefulness is for scales ranging from 1 : 10,000 to 1 : 40,000.

Stereo Photogrammetry as applied to Air Photo-topography.—There appears to be no reason why stereo photogrammetry should not improve and simplify the work of air photo-topography just as it has that of ground photo-topography. At the present moment the only method of obtaining the necessary precision of the data required is a mathematical solution of the positions of the camera in space at the ends of the base, coupled with a refinement of measurement of co-ordinates on the plate and of the focal length, which have not been attained so far in England. Professors Hugershoff and Cranz, of Dresden, claim to have secured, not only this precision of data, but a mechanical device for plotting direct from a stereoscopic pair. The instrument in question is called the autocartograph, and it is as yet impossible to say whether it will justify the claims made for it.

It is obvious that the problem will be simplified when the camera can be held in the aeroplane in any desired position relative to the earth. Even under existing conditions it should be possible to secure good relative determinations of height, using pairs of vertical photographs and a simple form of stereomicroscope. Recent experiments appear to confirm this possibility, and developments may occur shortly.

Section VI.—General Summary

All photographic methods of survey tend to increase accuracy of the outlines of detail in small areas, but often, if the trig control is not sufficiently ample, to a general loss of accuracy in relative position.

All the methods dealt with have their particular merits, but none should be considered satisfactory as the exclusive method for extended surveys.

They add so many more possibilities to the surveyor, and each method should be used as the situation demands.

Those who desire to study the subject, either as a whole or in part, more thoroughly than can be done in this short outline are recommended to read the following books:

Ground Photo-topography

Photographic Surveying, by Captain Deville (Ottawa, 1895).

Phototopographic Methods and Instruments, by J. A. Flemer (Chapman & Hall, Ltd., London, 1906).

The Use of the Panoramic Camera in Topographical Surveying, by James W. Bagley (*Bulletin* No. 657 of U.S.A. Geological Survey).

AIR PHOTO-TOPOGRAPHY.

Mapping from Air Photographs, by Lieut.-Colonel M'Leod, D.S.O. (H.M. Stationery Office, 1920).

Applications de la Photographie Aérienne, by L. P. Clerc (Doin et fils, Paris, 1920).

Applications de la Photographie Aérienne aux levées topographiques, by M. H. Roussilhe (Hallu, Paris, 1920).

Note sur l'emploi pour les travaux cartographiques des photographies prises en avion, by M. de Vannsay (Imprimerie Nationale, Paris, 1919).

STEREO PHOTOGRAMMETRY.

Neue Stereoskopische Methoden und Apparate, by C. Pulfrich (Jena), (Berlin, 1903).

Stereoskopisches Sehen und Messen, by C. Pulfrich (Jena), 1911, and other books and articles by the same author.

CHAPTER X

Aeronautical Photography

Introduction

During the Great War aerial photography rendered important services, both as a means of reconnaissance, by which the intentions of the enemy were detected, and as a means of studying the works he had erected, so that trenches, gun positions, new roads, railways, &c., could be included in our maps, and erroneous or obsolete details eliminated.

The value of aerial photography was realized long before the War; the first attempts were made as early as 1858, when M. Nadar took some successful photographs of Paris from a balloon. Its development in the British Air Service, however, dates from the formation of the R.F.C. in 1912. The progress made from that time up to the outbreak of war in August, 1914, was naturally very slow. However, the experience gained in those two years was invaluable, and contributed largely to the early success of the photographic sections in the field. Special experience in the actual type of work was essential, for the manner of obtaining a good photographic negative from the air differs entirely from the process for obtaining an ordinary landscape photograph, because of the position of the photographer in relation to the object to be photographed, and to the source of light. The different luminous rays coming from the object have to pass through several layers of air before reaching the lens of the camera. Reference to the influence of these layers of air on the photographic plate is made in Section IV, p. 421 (Plates and Films).

Aerial photography undoubtedly advanced during the War, with every other branch of aeronautics, reaching such a high standard of efficiency that it can now be applied to many peace-time purposes.

The various spheres of activity in which it can be successfully employed include: land survey, which offers the widest field of all (see Chapter IX on Photographic Surveying); town planning; transport plans for towns; location of watercourses, tracks, and ways of communication; coastal work, when it is necessary to locate wrecks, mines, sand-banks, or changes in the coast-line; dredging and research work in the sea; &c.

This class of photography, up to the present, has been developed exclusively for military purposes, and the details have been kept more or less secret. It is of interest now to state a few facts.

The outbreak of war found the British Air Service equipped with a few Press-type cameras and a portable developing box; these, however, were the foundation of what eventually turned out to be a gigantic photographic establishment, producing thousands of negatives and prints every day. The equipment of this establishment was evolved under war conditions. The pilots and observers, when taking photographs, were constantly engaged in aerial combat, or in evading anti-aircraft guns. They were thus prevented from giving their fullest attention to the handling of the photographic apparatus. It was realized that the photographic process needed facilities by means of which large expanses of country could be photographed daily, under the most rigorous conditions. This led to the introduction of automatic cameras. Before entering into the technical details of aerial cameras, the general statement may be made that, under the conditions prevailing, it was essential that the camera should fulfil certain requirements in order that any man, without previous photographic experience, might operate it with a minimum of instruction. These requirements were:

(1) simplicity,
(2) compactness,
(3) lightness in weight.

In the development of plates, printing, &c., the fundamental principles of photography are as important in this as in any other class of work; it should be noted that they should, if possible, be applied with extra care.

The subject of the following pages is the evolution of aerial photography, with special reference to the camera, camera mountings, plates, films, light filters, and lenses; the methods employed in the taking of the photographs are also explained in detail.

Section I.—The Development of Aeroplane Cameras

The first camera constructed entirely for aerial work, embodying the essential details which would meet the requirements already explained, was the A type, which was essentially of the hand-held type. It was constructed with a polished mahogany body, brass bound. The lens, usually of 8-in. focal length, focused on and fixed at infinity; focal plane shutter of the old Goertz-Anschutz type, with adjustable aperture. Plates, size 5 in. × 4 in., carried in Mackenzie-Wishart envelopes, and changed in the adaptor of the same make, which is a most convenient form of plate-changing apparatus, and does away with the necessity of mounting each plate or pair of plates in the usual dark slides, which are heavy and bulky. It is necessary to avoid these factors in aerial work. Each plate is enclosed in a light-tight envelope, which, for exposure, is placed in the adaptor; the adaptor is fixed in position on the camera body. By drawing out the slide of this adaptor, the plate is automatically uncovered for exposure, and is re-covered after exposure by closing the slide. An inspection window is fitted into the hinged door of the adaptor. Through this window it can be seen whether the envelope is opening properly. For holding the camera, straps are provided, through which the hands are passed, in order to obtain a firm grip. The sight is a simple brass tube with cross wires. The three specially good features of this type are the "foolproof" devices, acting as follows:

(1) Rendering it impossible to remove the M.-W. envelope until the slide is properly home.
(2) Locking the shutter winding gear when the plate is in position for exposure.
(3) Locking the release until the slide is fully drawn.

It is, however, impossible with this type to obtain photographs suitable for overlapping strips or mosaics, &c., owing to the distortion produced by the varying angles at which the camera is held.

The necessity for vertical photographs resulted in an attempt to fix the camera rigidly on the outside of the fuselage. Many useful results have been obtained in this manner, in spite of the obvious difficulties under which the pilot worked. It was nevertheless soon apparent that something more simple in operation had to be designed, leaving the pilot free to manœuvre his machine. This resulted in the introduction of the C type.

C Type.—This is a semi-automatic camera; actually it is the body of the A type, fitted with a semi-automatic plate-changing device, in place of the Mackenzie-Wishart slide.

This embodies a means whereby the single operation for changing the plate also resets the shutter. To protect the plates from the light during the shutter-setting operation, a mask plate is automatically placed between the lens and the plates. Plates, size 5 in. × 4 in., in metal sheaths are used, eighteen being carried in each of the magazines provided. After exposure, each plate is passed from the top (or full) magazine into the lower (receiving magazine).

All the operator has to do in order to take a series of photographs is to push the operating handle in until the word " set " appears on the indicator, then bring it back to normal, and pull the release cord; continuing these operations alternately until eighteen exposures have been made. If further exposures are required, he closes the magazines, replaces the lower one by the top (now empty), and inserts another full one.

The C type was undoubtedly the pioneer of the semi-automatic type aerial cameras, and it will be noticeable that some of its main features remain in the most modern types. It did signal service before it was superseded; its principal failure was the inefficiency of the cord which operated the shutter. This was especially noticeable during the winter months, when any moisture on it froze at high altitudes, rendering it easily broken. The additional head resistance set up by its position outside the fuselage was also a disadvantage. To overcome the latter, it was necessary to fit the camera inside the aeroplane, and as there was no room for it in the pilot's or observer's cock-pits, the only solution was to redesign the camera so that it could be operated by means of distant controls. The modifications necessary for this purpose were incorporated in the E type.

E-type Camera.—This type was, with the exception of the magazines, constructed entirely of metal. A new and very important feature was its adjustable lens mount; the shutter remained the same (Goertz-Anschutz, as used in the A type). The plate-changing apparatus in this camera only overhangs the body on one side, thus considerably reducing the overall size.

The metal disc which shaded the plates from the light during the resetting operation on the C type was replaced by an external lens cap, operated by means of the exposure release trigger, so arranged that the lens is covered until the release trigger is fully depressed. The cord used on the C type was replaced by a ratchet gear, which

enabled it to be operated from a distant control by means of an endless cord.

The E type soon became obsolete. The work of the pilots and observers was ever on the increase, as also were the enemy's efforts to prevent our men from securing photographs. It was therefore necessary to design a camera which required even less attention from the pilot.

L-type Camera.—The L type was a great advance on all previous models. This type can be fitted in any desired position, either in or outside the fuselage; it can be worked mechanically or automatically at will, and is provided with locking means whereby the camera whilst working automatically cannot be operated mechanically, or vice versa. Whilst working automatically the only work devolving upon the pilot is the depressing of the release lever to actually take the photograph. The first models were fitted with a plunger release on the camera; this, however, was not used, owing to the movement caused by it at the moment of exposure. A Bowden release was used in preference. The plunger, in many cases, was cut off in order to remove the temptation to use it, its use being so fatal to sharp definition. When working on power, the return action of the release lever sets the mechanism again in motion for changing the plate and resetting the shutter, the time occupied by this operation being about four seconds, after which it is ready to take the next photograph.

The camera is also provided with locking means, so that whilst the machine is automatically changing the plate, &c., the shutter trigger for releasing the shutter cannot be operated. The action of the camera mechanism when running automatically is as follows.

An air screw is rotated by air pressure, and with it the flexible shaft transmitting the power through a worm drive to a worm wheel and pinion engaging with a larger mutilated toothed driving wheel. The larger driving wheel makes one complete revolution before reaching that portion of the wheel from which the teeth have been removed. This revolution completes the operation of changing the plate and resetting the shutter. The air screw is then free to rotate without actuating the mechanism, and will continue to do so until the operator again releases the shutter. The return movement of the release brings a leaf spring to bear on the pin mounted on the mutilated wheel, and moves it to a position which will allow of the pinion automatically engaging with the teeth of the large driving

wheel, which then makes another revolution, completing the cycle of operations.

The magazines are placed in the same position as on the original C type; the shutter is the same, viz. focal-plane Goertz-Anschutz type, as in previous types. Plates are protected from light during the changing operation by an internal lens cap, which is mechanically removed during exposure by the lever release.

The propeller or air screw may be fitted to the aeroplane in any suitable position by means of a bracket in conjunction with a flexible drive. It is usually placed on two uprights fixed into the fuselage in a position immediately in rear of the observer's seat. When it is desired to operate the camera by hand, the pin is removed from its position on the operating handle and placed through a hole in the driving wheel, thereby locking it, and at the same time freeing the handle from the driving mechanism. The lever release, which is fitted to the uprights in the interior of the pilot's cock-pit, also serves as an indicator to show the number of plates exposed.

Although the L type was by no means an ideal camera, it stood up to the rigorous tests of active service over a longer period than any other British, Allied, or enemy aerial camera; even when replaced by the L.B., its main features were retained.

Film Cameras.—During this period of evolution of the aerial camera, the question of film cameras was not being overlooked. Before the L-type design was completed, efforts were being made to produce an automatic film camera.

The F type was the first film camera; it was automatically driven by an air screw, or propeller. In this case, however, the driving propeller was fitted to the camera direct. This necessitated its being fitted to the outside of the aeroplane (see fig. 1).

The speed was regulated by governors controlled by a lever which travelled through the slot marked with the number of pictures per second as required. Mounted on top of the camera was a combined compass and altimeter, the readings of which were automatically recorded on each exposed film.

This camera gave very unsatisfactory results, which probably did much to influence the Photographic Staff of the British Royal Air Force in its determined stand against film cameras, a policy which was amply justified by subsequent results. Although many claims were made in different quarters, it can be said that on 11th November, 1918, there was not a reliable aerial film camera in existence. This statement is not made through any prejudice against the film; on

Fig. 1.—F. Type Camera fixed to Aeroplane Fuselage

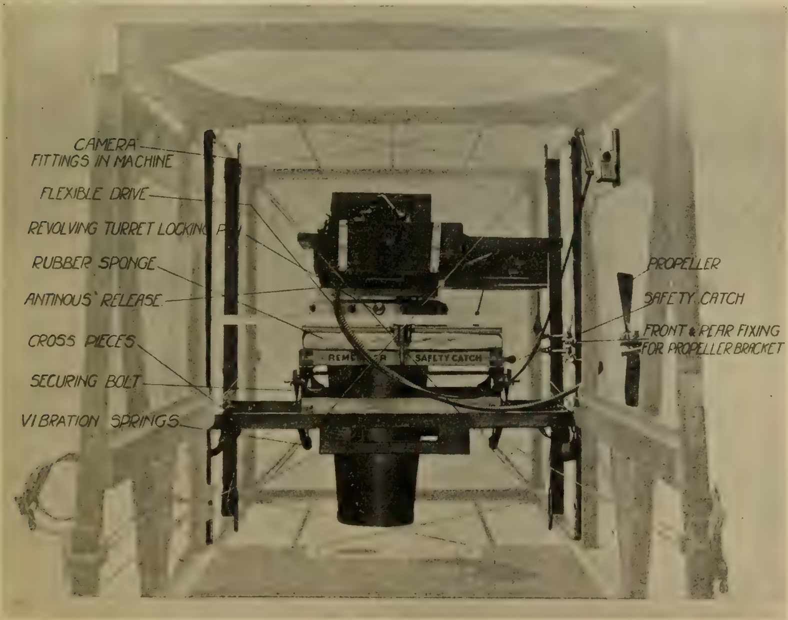

Fig. 9.—B.M. Type Camera mounted in an Aeroplane

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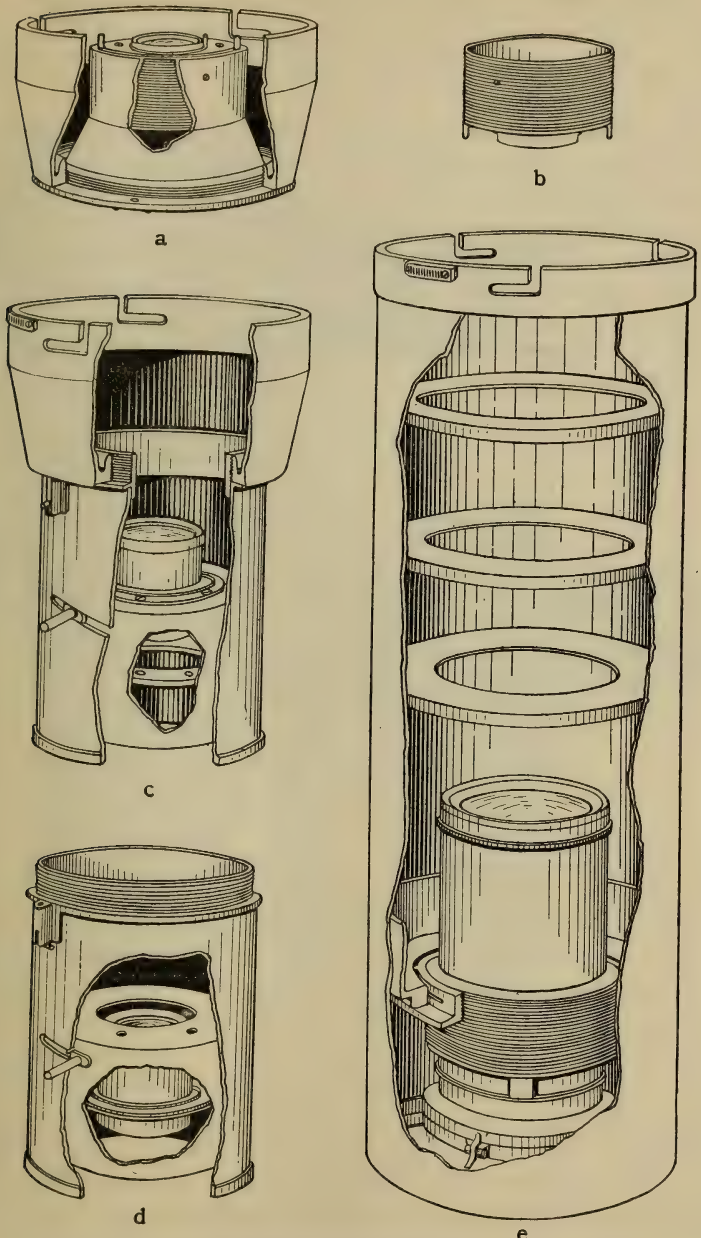


Fig. 2.—The Interchangeable Lens Tubes used on the L.B.-type Camera

the contrary, it is thought that the film will eventually replace the plate in aerial work. With experience gained during the War, there is no doubt that an aerial film camera of perfect design will soon appear.

L.B.-type Camera.—The L.B. type, a modification of the L type, is of the semi-automatic kind, and designed either for power or hand actuation, at the will of the operator. As in the case of the L type, the exposure of the plate and its subsequent change and the resetting of the shutter are affected by a single movement of the lever release.

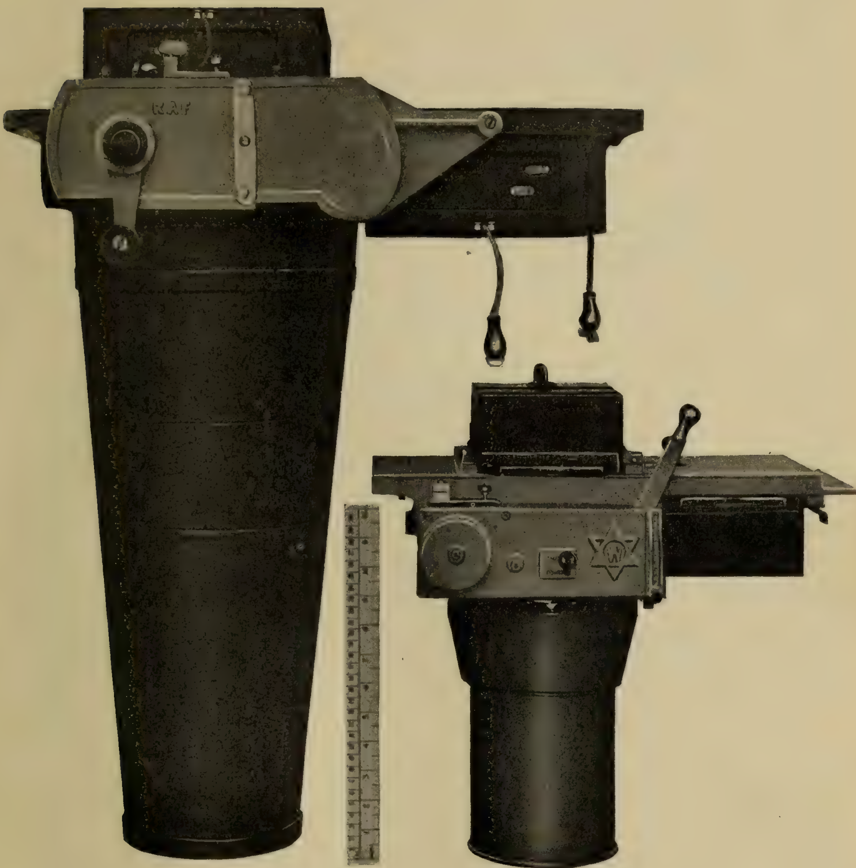
The shutter is of the focal-plane type (self-capping). The shutter box is constructed as a separate unit, and may be removed from the camera without displacing any other part; this is considered a great improvement over previous types. Hitherto shutters have been difficult of access to make minor repairs or adjustments. There is no doubt that fixed shutters gave more trouble than any other part of the camera. The feature which gives it the greatest advantage over the previous models is the system of interchangeable lens mounts, which enables the camera to be utilized for every class of work. Lenses of focal lengths varying from 4 in. to 20 in. are provided (see fig. 2).

(*a*) shows 4-in. lens, sleeve, and adaptor.
(*b*) shows 6-in. lens and sleeve.
(*c*) shows 8-in. lens, sleeve, and adaptor
(*d*) shows $10\frac{1}{2}$-in. lens and sleeve.
(*e*) shows 20-in. lens and tube.

In the 20-in. arrangement, attention is drawn to the baffle plates, also the system for locking the lens. Another feature is the movable guide, which may be brought into action to remove quickly the top magazine in the event of a jam; also the shutter slit adjustment on the outside of the camera. Other details are almost identical with those in the L type, and need no further explanation.

So far, the models described used 5 in. × 4 in. size plates, from which it is usual to make enlargements. It is obvious that, in many photographs taken from aircraft, vibration of the machine causes unsharpness and occasionally signs of movement. Enlargements from such negatives tend to exaggerate the existing defects. The interpretation of aerial photographs is simplified when contact prints with large detail are used, hence the demand for a larger plate.

B.M.-type Camera.—The B.M. (fig. 3) is an enlarged model



(a) (b)

Fig. 3.—Aerial Cameras, Types (*a*) B.M. and (*b*) L.B.

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of the L.B. Plates, size 18 cm. × 24 cm., are used in this type. The mechanism is slightly modified, but in general principles it is the same. It has one great disadvantage, viz. its weight and size compared with all previous models. The L.B. with one magazine and 18 plates weighs 52 lb., whereas the B.M. with one magazine and 12 plates weighs 85 lb. The weight increases with extra magazines as follows: for every L.B. magazine and 18 plates, 4 lb.; for every B.M. magazine and 12 plates, 16 lb.

Like the L.B. it is constructed to take lenses of various focal lengths, but in this case from 7 in. to 36 in. For fine detail work it is a very fine camera. Fig. 4 shows a B.M. result from 10,000 ft.

The more important of the automatic plate cameras having now been dealt with, a brief description of some of the simple models which were made in the field during the War may be of interest.

W.A.-type Camera.—The W.A. type was designed for wide-angle work, that is to say, for covering large areas. It consisted of a simple metal cone fitted to a focal-plane shutter; plates, size 8½ in. × 6½ in., carried in double dark slides. The type of slide fitted with the venetian-blind principle should be used in preference to the ordinary commercial type where the slide is drawn out to its full length. The latter is very inconvenient when mixed up with the wires of an aeroplane in the usual limited space. Lens, either 8-in. or 10-in. fixed focus (infinity). The release used was known as the "stirrup" release. As in the case of the automatic camera, a Bowden wire must be employed. Excellent results may be obtained, especially where large areas are required on one plate. (See fig. 5, a typical result taken from an altitude of 10,000 ft.)

B-type Camera.—The B type is designed for oblique aerial photography, a type of photograph which undoubtedly appeals much more to the public from a pictorial point of view than the vertical, although the latter is of greater value for mapping, town planning, survey, &c. The only point in which this type differs from the W.A. type is in its lens, which is of longer focal length; a 20-in. lens is the one commonly used, but in some cases it may be much longer, even up to 47 in. With this type of camera some of the most magnificent oblique photographs were taken (see fig. 6).

Hand-held Camera.—It is necessary to go back to the introduction of the first fixed camera, which, without some explanation, might be thought to have entirely replaced the hand-held camera. This is not so; there are many purposes for which the hand-held camera can be, and is still used, such as oblique views of large

mansions, churches, and other points of interest; photographing of clouds; also other machines in flight. If fitted with the necessary instruments for recording angle of tilt, they may be used for mapping purposes.

A-type Camera.—The A type was used for some considerable time for spotting and oblique work, but was eventually superseded, owing to the warping of the wood causing movement of the lens in relation to the focal plane, thereby shifting the focus. This trouble was more noticeable in tropical climates. It was replaced by one constructed entirely of metal, the P type (fig. 7).

P-type Camera.—The body of this camera is machined from an aluminium casting of tapered cylindrical shape, at the top of which is a rectangular platform provided to take the shutter and winding mechanism, also guides for the dark slide. The lens is usually of 10-in. focus, and fixed to a flange in the lens tube: see (*a*) in fig. 7. It is focused on and fixed at infinity. Two handles are provided, one a "spade grip" handle, mounted on the left-hand side of the lens tube, and a straight bar handle on the lower right-hand corner of the shutter platform. For convenience in packing, the latter handle may be folded. The shutter is a focal-plane blind, self-capping; the slit adjustment is made by means of a small knob: see (*b*) in fig. 7. The width of the slit adjustment is indicated on a dial. The sight is a brass tube fitted with cross wires at each end, placed on the lower edge of the camera body. This position is found to be the most satisfactory; it reduces to a minimum the movement of the operator (when taking aim) outside the fuselage of the aeroplane, where there is no protection from the tremendous rush of air. The plate-changing is done by means of a Mackenzie-Wishart slide. The method of operating this slide is fully described on the A-type camera.

The Ideal Camera.—The general tendency of designers of aerial cameras now is to produce a camera which will fulfil the requirements of the surveyor. From actual experience it is found that, unless the photograph is sufficiently sharp in its definition, few, if any, of the methods employed by the surveyor can be used with any success. If, however, the distinction between the photographer and the surveyor is maintained (consistently with their necessary co-operation), the photographer will produce the right class of photograph.

The foregoing pages describe the actual development of the aerial camera up to the end of the War. The following is a brief

Fig. 4.—Aerial Photograph of St. Paul's Cathedral, taken with B.M. Camera from height of 10,000 feet

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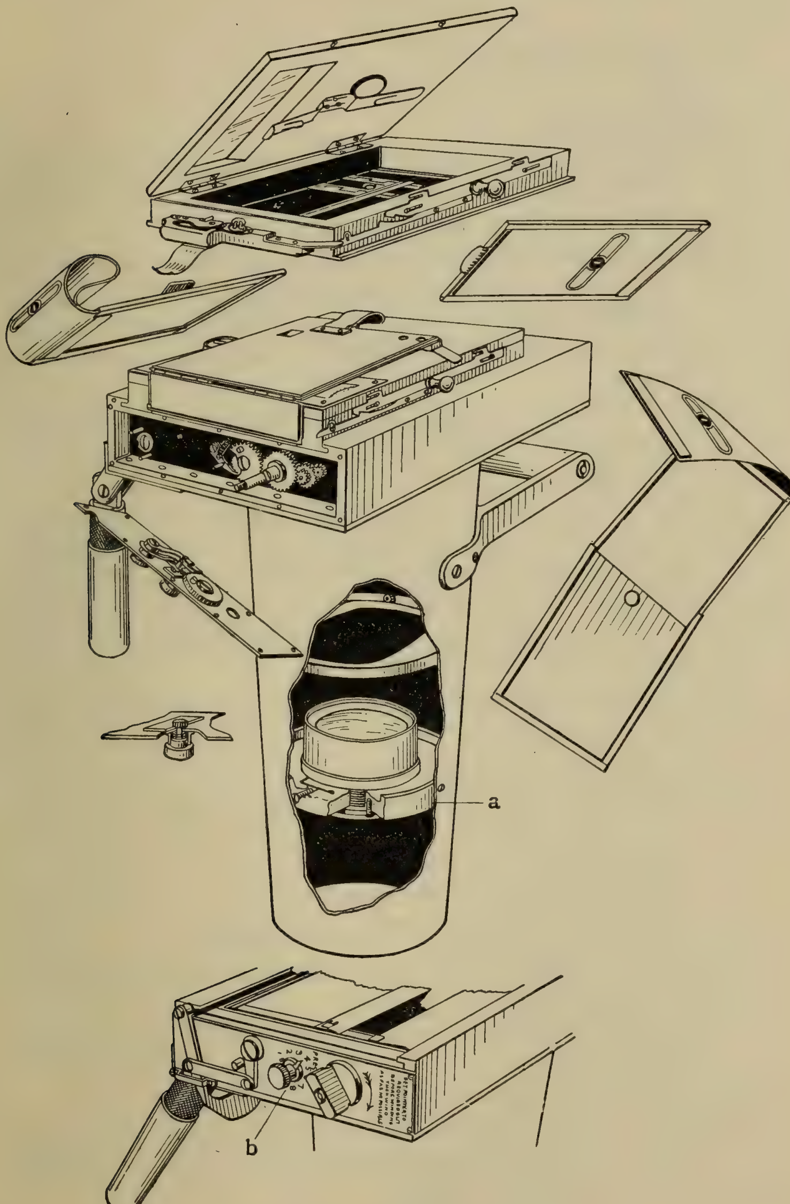

Fig. 7.—P-type (hand-held) Aerial Camera

description of what is considered the ideal to be aimed at in future designs:—

The camera ought to be—

(*a*) light,

(*b*) small in bulk,

(*c*) automatic in operation both in plate-changing and shutter setting; also in continuous exposures at fixed intervals for overlapping purposes.

(*d*) The centre of gravity should be maintained constant during operation by means of a compensating device to counteract the movement of weight of the film or plates.

(*e*) The camera should be adapted to take lenses of any focal length.

(*f*) The sensitive material, i.e. plates or films, at the moment of exposure ought to be held stationary and flat in the focal plane.

(*g*) The shutter should be of an efficient between-lens type.

(*h*) The size of the picture, which to a great extent is controlled by the work in hand, should be variable, if possible, from say 7 in. × 7 in. to 3 in. × 7 in., with sufficient margin on the sensitive material for items described at (*i*) to be recorded on each exposure.

(*i*) Provision should be made for recording automatically upon every exposure—

(1) the compass bearing,

(2) the angle and direction of tilt of the optical axis from vertical,

(3) the date and time,

(4) the number of the exposure,

(5) the optical centre of the photograph.

(*j*) The focal length of the lens should be accurately measured and engraved on the mount.

(*k*) The camera should be stabilized by some means, such as the gyroscope.

(*l*) It should be simple in operation and reloading.

(*m*) Means should be provided for making either single exposures, or an automatic succession of exposures ranging from 1 to 12 per minute.

Fig. 5.—Photograph taken with W.A. Type Camera

PLATE XVIII

Fig. 6.—Oblique Photograph taken with B. Type Camera

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Section II.—Camera Mounting on Aircraft

The mounting of aerial cameras is a factor equal in importance to the efficiency of the lens. Without a perfect mounting, it is impossible to secure good results. A few words on exposing with the hand-held cameras (previously described) are first necessary.

When taking aerial photographs, the arms and body of the photographer must be visualized as the mounting. The first and most important function of any camera mounting should be to absorb the constant vibrations of the aeroplane. It is necessary that the photographer, when operating, should ensure that his arms do not touch the fuselage or any structure of the aeroplane, thereby transmitting the vibrations to the camera.

The method of holding the camera should be to firmly grip the handles with both hands, keeping the elbows pressed into the sides, and the back (or top) of the camera pressed to the forehead, in order to arrive at efficient sighting. When in alignment with the object to be photographed, very gently contract the fingers on to the exposing trigger; avoid transmitting any violent motion; the action should be similar to the operation of firing a rifle, i.e. the trigger should be *squeezed*.

The fixed camera is a more difficult problem. Throughout the War, the mounting question was constantly to the fore.

Firstly, it is advisable to realize that at that time there existed two distinct schools of thought, one being entirely for the fixed camera (with no attempt to absorb vibration), and the other in favour of a mounting adapted to absorb shock and vibration.

On active service, there was much to be said for the rigid fitting; the method is simple, and *sometimes* effective. There are, however, two distinct disadvantages of a fixed mounting, particularly on the outside of the fuselage, viz. (1) the loss of speed by the aeroplane in consequence of the additional head resistance occasioned by the camera, and (2) the direct transmission of mechanical vibration from the aeroplane to the camera, resulting in the deterioration of sharpness in the photograph. The failure in sharpness is usually defined by vibrational bands across the plate (fig. 8). This is more particularly noticed when photographs are taken from an aeroplane in which the engine is firing erratically; for instance, a missing cylinder produces a distinct mechanical vibration through the structure of the aeroplane, which causes a tremor across the resultant negative each time an exposure is effected.

In the first mounting for the A-type camera an important discovery was made, viz. that a fixed mounting must be sufficiently stable to prevent any whip. Similarly, when the shock-absorbing component is employed, it is obviously necessary to ensure that no part of the camera should be in contact with the rigid portions of the mounting.

Since the cessation of hostilities, with more time available, experiments have definitely proved that the best form of mounting is to be found in the shock-absorbing type.

The first attempt to damp the machine vibrations was made with the introduction of the E-type camera; four sponges were fitted to the mounting, each forming a bearing surface for the camera. Two more were placed through a hole in the floor in order that the lens tube could be stabilized between them.

This was followed by a mounting known as the L Tray, which came into use with the L-type camera.

From time to time various modifications were made, all of which might appear to be of small intrinsic value, but in point of fact were details of the utmost importance in future design. The original tray was fitted with rubber sponge contained in bags which were assembled into two boxes. After various trials it was found that the camera vibrations developed into a swing, causing circles of unsharpness on the photograph. To obviate this, nose-pieces were fitted to steady the lens mount, but did not prove entirely satisfactory. Further experiments proved that too much rubber in the bags allowed the camera to swing, even when the nose was stabilized. A new form of support was then introduced, consisting of bags containing blocks of wood which had only a thin layer of rubber on the top surface to insulate the camera from the wood. This considerably increased the mechanical stiffness of the mounting, while retaining the same vibration damping principle.

Subsequently a form of spring mounting was introduced which had a parallel motion, converting all vibrations into a more or less vertical movement, which is not photographically destructive. The springs are subject to a simple adjustment to compensate for the weight of any particular camera.

It is advisable to still further isolate the camera from direct contact with the solid portions of the mounting. This should be accomplished by placing rubber between the adaptor and the mounting. Numerous adaptors are provided in conjunction with this mounting, designed to carry the different types of cameras. Fig. 9

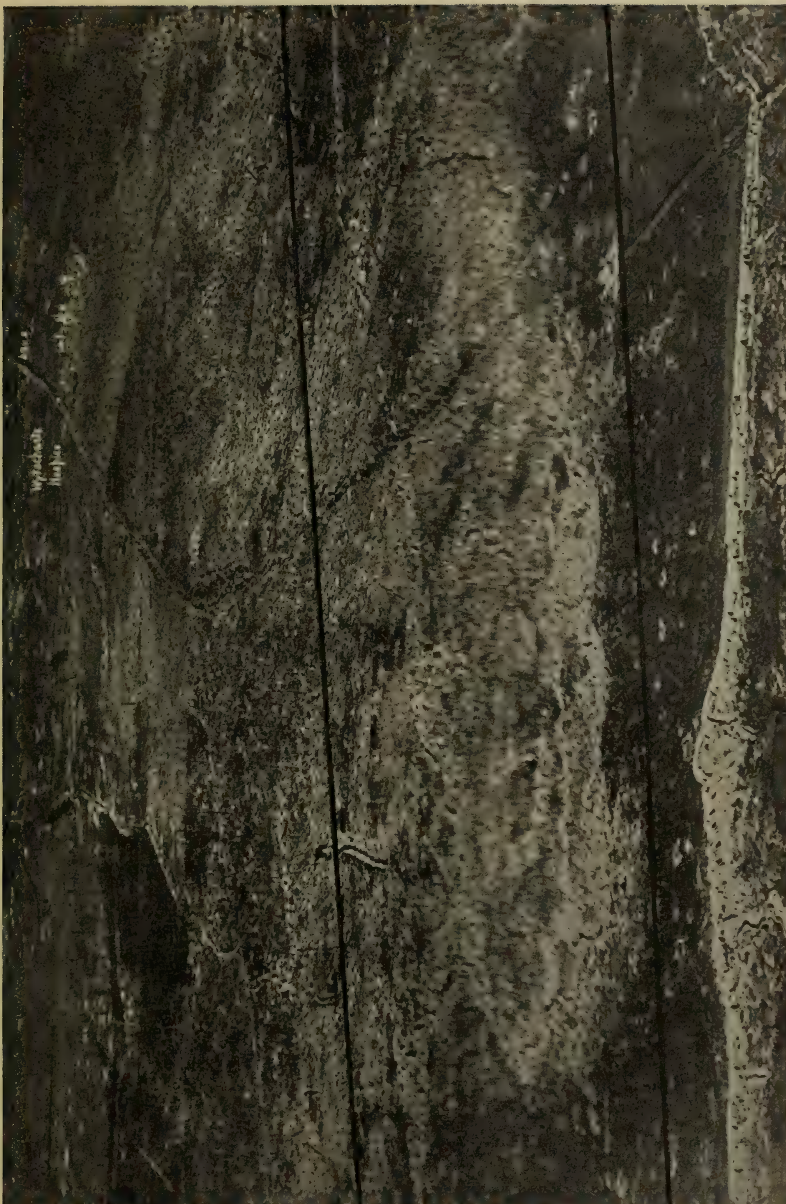

Fig. 8.—Oblique Photograph illustrating the Effects of Vibration

Facing p. 414


Fig. 10.—Flying over Lights to test Camera Mountings

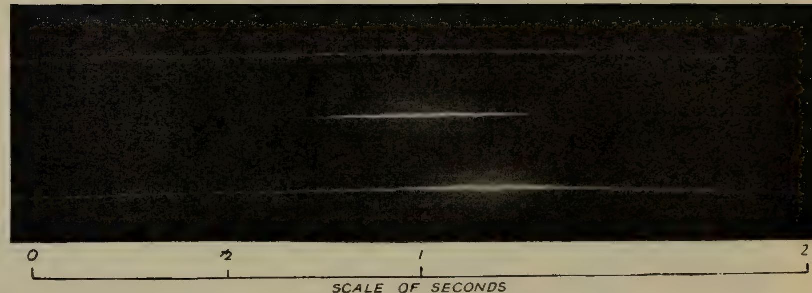

Fig. 11.—Good Mounting—slight vibrations

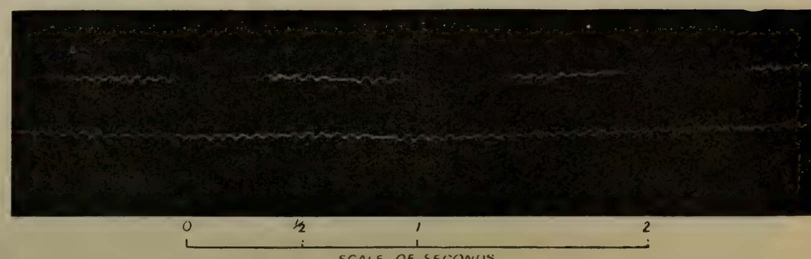

Fig. 12.—Bad Mounting—excessive vibrations

Facing p. 415

(facing p. 406) illustrates the B.M. type in the Turret adaptor. This camera may be swung round into any position to facilitate the changing of magazines. This mounting, although not perfect, is very efficient.

The method of testing camera mountings is of interest, and is briefly described as follows.

A group of three lights is placed on the aerodrome about ten yards apart, the centre light being fitted with an automatic device for flashing the light on and off for definite and known periods. The aeroplane, fitted with a camera which is on the mounting to be tested, is flown over these lights at night, the shutter of the camera remaining open. From the results it is possible to determine the number of vibrations which have occurred per second. An illustration of the method and some of the results are shown in figs. 10, 11, and 12.

Section III.—Lenses

The lenses which have chiefly been used are the Ross Aero, Ross Express, and the Cooke Aviar. The aperture is usually F 4·5, the focal lengths in general use being 4 in., 6 in., 8 in., 10 in., 14 in., and 20 in. The 10-in. focal length for ordinary purposes gives very good results. The choice of lens, however, depends largely upon the class of photograph required, whether of a large area with correspondingly small detail, or of a small area with correspondingly large detail.

The most important points with which an aerial photographer must be fully acquainted are: focal length and scale, angle of field of vision, and working aperture.

The equivalent focal length of a lens is the distance of the point of focus from the rear nodal point of the lens.

The focal length is a most important factor; it decides the scale of the picture. Two photographs taken from precisely the same altitude, one with a long-focus and one with a short-focus lens, will vary in exact proportion to the focal lengths of the two lenses.

When it is desired to determine the scale of an aerial photograph, it is only necessary to know the focal length of the lens and the height from which it was taken. For example, it is desired to find the scale of a photograph taken with a 10-in. lens at a height of 5000 ft. (F and H must be in like terms.)

$$S = \frac{F}{H} = \frac{10}{5000 \times 12} = \frac{1}{6000} = \text{R.F.}$$

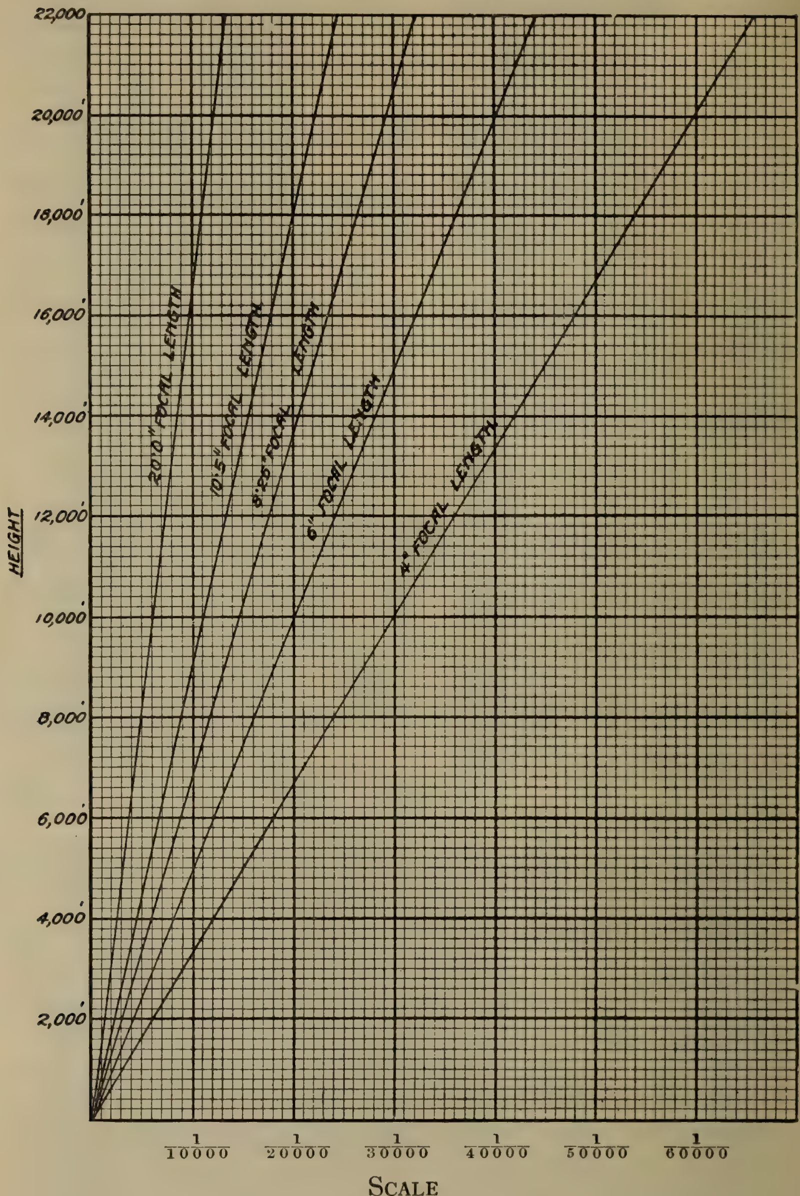

Fig. 13.—Graph for finding the Scale of Aerial Photographs

A graph for determining the scale, &c., will be found useful (fig. 13). This, it must be understood, applies only to photographs taken when the optical axis is absolutely vertical.

To find the area covered by an aerial photograph, multiply both sides of the plate by the reciprocal of the R.F. (e.g. by 6000 in above example); this gives the linear measurement of both sides, the area being found by multiplying the two together. Another simple method is by the following equation:

If f is the focal length (in inches),
h, the height (in feet),
W or L, the length or breadth of the plate (in inches),
P, the linear measure of ground covered (in feet),

$$\text{then } P = \frac{h \times W \text{ or } L}{f}.$$

Angle of Field of Vision.—Every lens displays, on a sufficiently large focusing screen, a large or small circle, with a fairly sharp outline. The diameter of the circle always remains the same; it is not affected by the change of stops.

For short, the angle of field of vision is spoken of as field of vision. This circle of illumination is, however, not sharply defined right up to the edge, and a distinct falling off of light is apparent towards the circumference. Therefore, only a portion of this surface can be made use of for the picture; this portion is known as the picture field. By the use of suitable stops, the picture field could be enlarged, but, for obvious reasons, in aerial photography the use of stops is very limited.

In order to work at full aperture, the size of the picture must be taken within the well-defined part of the field of vision.

With most lenses, the longer the focal length, the smaller the angle of field of vision, so that a lens of a certain size must be made use of, and the focal length chosen in relation to the angle of field of vision. The serviceable picture angle depends upon the construction of the lens (see fig. 14).

Working Aperture.—In aerial photography, where the amount of exposure is limited by the movement and vibration of the aircraft, the amount of light allowed to pass through the lens to the plate should always be the maximum, and since the subject to be photographed is practically in one plane, the necessity for depth of focus does not arise. For this reason, most of the lenses constructed for aerial photographic purposes have fixed apertures.

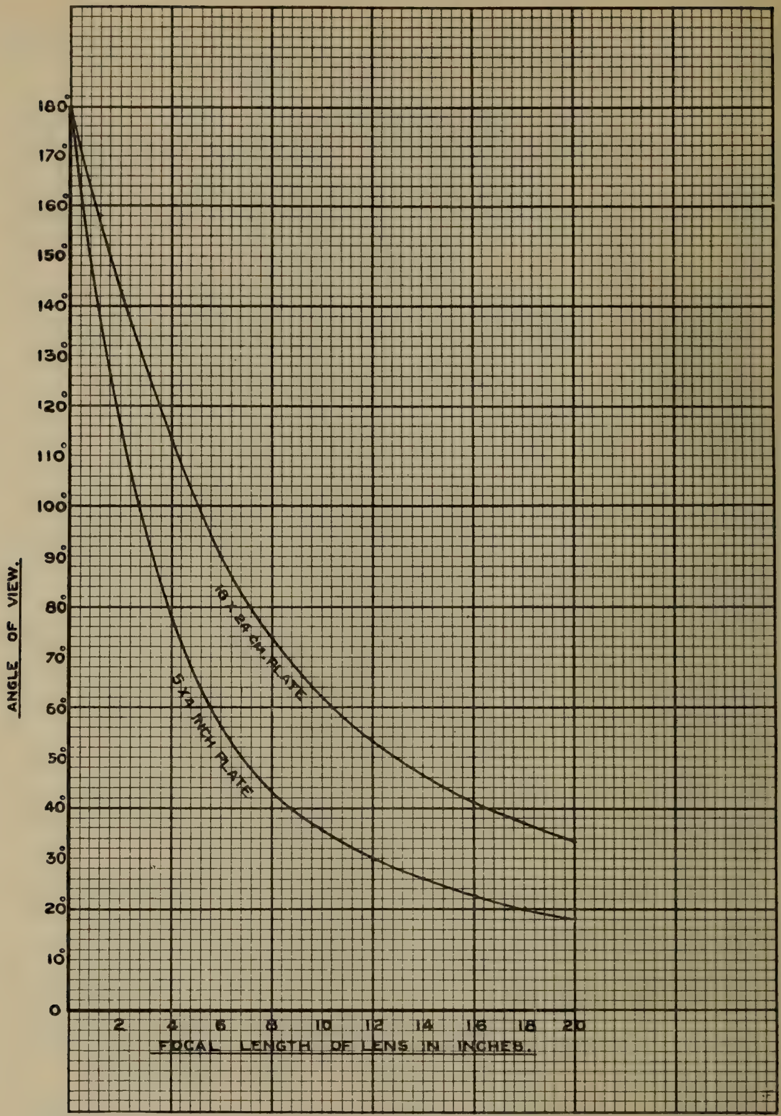

Fig. 14.—Graph showing Angle of View of Lenses up to F = 20 in.

It is naturally a matter of great importance that the aerial photographer should possess a thorough knowledge of the light strength of his lens, in order to be able to determine the exposure necessary when working at its full aperture, also when stops are used. In

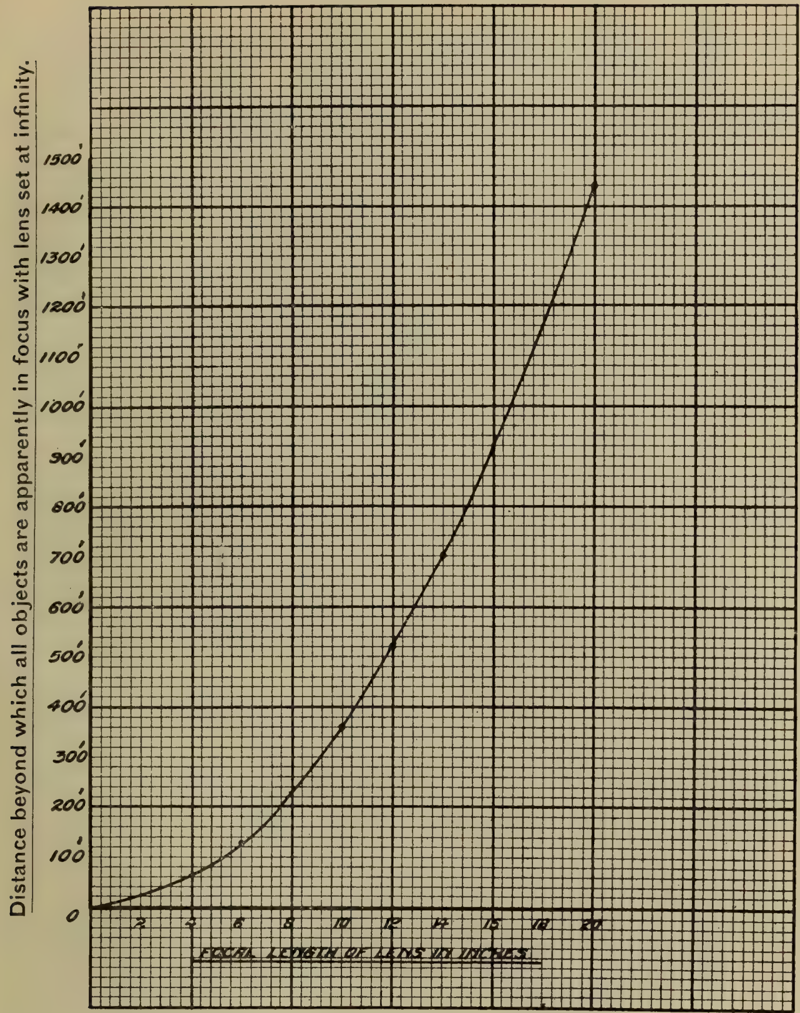

Fig. 15

aerial photography, however, the necessarily very rapid exposure limits the use of stops, so it is usually better to work at full aperture, and with the highest possible shutter speed, thereby limiting the effects of movement.

The lenses mentioned on p. 415, which were constructed and produced in large quantities during the War, may be used with complete confidence (figs. 15, 16).

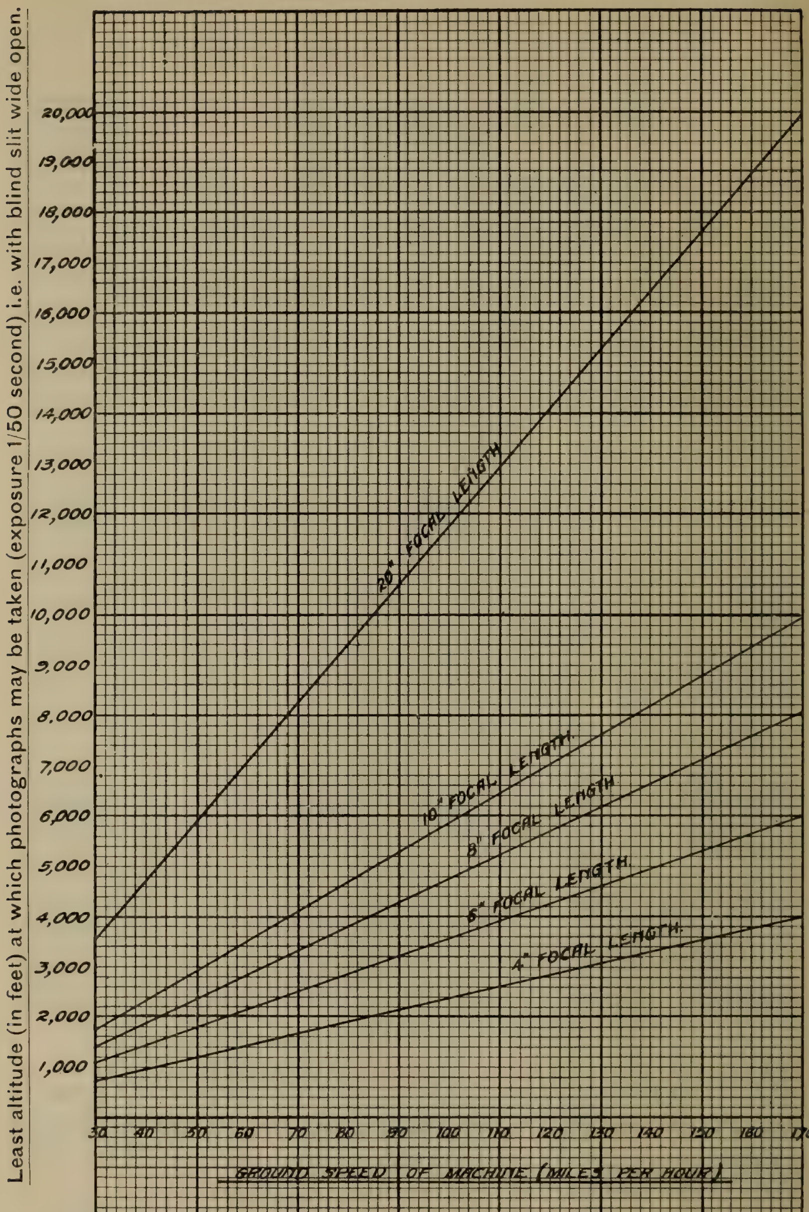
Least altitude (in feet) at which photographs may be taken (exposure 1/50 second) i.e. with blind slit wide open.
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
20" FOCAL LENGTH
10" FOCAL LENGTH.
8" FOCAL LENGTH
6" FOCAL LENGTH.
4" FOCAL LENGTH.
30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
GROUND SPEED OF MACHINE (MILES PER HOUR)

Fig. 16

Section IV.—Plates and Films

The air is not an absolutely transparent medium. It causes

(1) the absorption of certain colours,

(2) the refraction of light at different angles.

Thus, in photographing a landscape by means of an ordinary plate, it will be observed that the distance contains no detail. The length of range practicable for obtaining good photographs with clear detail in the distance depends then upon the greater or less transparency of the different layers of air, that is to say, especially upon the greater or less amount of dust or water particles contained in these layers.

An ordinary photographic plate is particularly sensitive to the violet rays, while the effect of absorption is most marked with other colours. It is then absolutely necessary, in order to obtain a good aerial photograph, to employ plates that are extremely sensitive to colours other than violet, so that these colours may make an impression. To obtain still better results, a screen is employed (see Section on Filters, p. 424).

These facts led to the general use of the panchromatic plate, undoubtedly the most suitable. In addition, it will be noted that there is a distinct advantage obtained by the better rendering of the tone values corresponding to the colours of the landscape. Plates sensitive to the less refrangible rays have the further advantage of producing better results in misty weather, and in taking photographs from a distance. On the one hand, in fine weather, distant objects are shrouded by an atmospheric haze, caused by the scattering of the violet and ultra-violet rays. The effect of these rays is eliminated by making them pass into a yellow filter, which absorbs them, thereby preventing their action on the plate.

On the other hand, in slightly misty weather, the red rays are practically the only ones transmitted; a plate sensitive to reds, exposed through a filter which in itself absorbs or weakens the other rays, will give a useful result, whilst ordinary plates would give nothing.

In general, to meet the requirements of the aerial photographer, a plate should be capable of giving a high contrast with a very short exposure. The speed of the plate should be the maximum, the grain small, and the emulsion sensitive to all colours. The glass upon which the emulsion is coated should be flat and very carefully

cut. Badly cut plates may, and frequently do, cause a jam in the changing mechanism.

Films.—The use of films in the air, up to the present, has been limited. The main development of aerial photography having taken place under war conditions, the exigencies of the Service were necessarily the first consideration.

The introduction of the F-type camera, as already stated, provided the initial attempt to use the film in the British Air Service, but was far from successful. Under the conditions ruling, the average risk of failure could not be taken. For a time, attempts to use film had to be curtailed, but in 1918 there was again a tendency to revert to it. The film was not used to any great extent either by the Allies or their adversaries, although both sides tried hard to produce an efficient film camera. Not merely are there mechanical difficulties when using film cameras, but it cannot be said that there exists an emulsion on film base equal to that on glass. Whilst it is admitted that in the air the film has many advantages, these are quite outweighed by the many difficulties in handling material of this nature in development. Given the necessary time for research, both with regard to the emulsion and the methods of mechanically developing and drying, the film will eventually take its place in aerial photography.

Section V.—Stereoscopic Aerial Photographs

An added interest and usefulness is obtained from viewing aerial photographs stereoscopically. Contours and outstanding features may be examined in relief, and the interpretation of the photograph simplified. The comparative heights and solid appearance of the objects readily disclose and explain doubtful forms, while the clearness with which contours and depressions show up greatly assists in the construction of form lines in map compilation.

Steroscopic effect or relief is obtained when viewing, by means of lenses or prisms, two photographs of the same object, taken from slightly different points of view, and mounted side by side. For this work it is usual to use a camera specially constructed with two lenses, with a separation of about 2½ in., which is the average distance between the human eyes. Owing to the different angles of view taken by the two lenses, the result is similar to that seen with both eyes open.

When viewing the ground from high altitudes, there is apparently

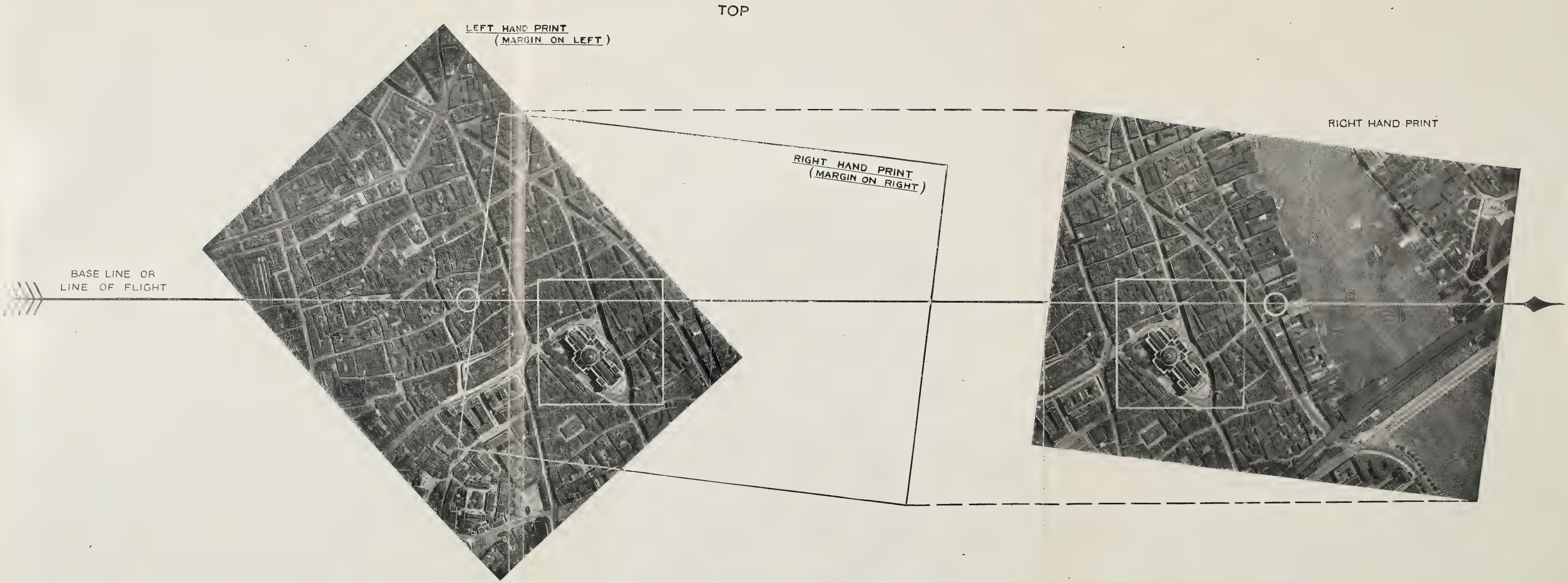

Fig. 17.—Method of Preparing a Stereoscopic Pair of Photographs

Facing p. 422

no stereoscopic effect, the angle made by the eyes being too narrow for the distance from the object. It is therefore necessary to increase the separation of the lenses; the higher the flight, the greater must be the separation.

The results giving the most natural appearance are obtained when the two photographs overlap each other by 75 per cent; with less, the effect is much exaggerated, though sometimes this is an advantage.

To find the interval *in seconds* required between exposures to obtain the necessary overlap:

If T is the interval in seconds between exposures,
L, the length or width of the plate (in inches),
W, the width of overlap required (in inches),
H, the height (in feet),
V, the ground speed (feet per second),
F, the focal length of lens (in inches),

$$\text{then } T = \frac{(L - W) \times H}{V \times F}.$$

Seldom is it found that a series of aerial photographs are taken on the same line of direction. Therefore, before mounting up the two prints, the line of flight or base line must be found. This is done by superimposing the two photographs (the centres of which should be first marked). Then move them apart, taking care not to change the relative positions. Fig. 17 illustrates this. A line AB is then drawn through the centres of the two prints. This is the base line or line of flight, all points on which should be on a line parallel to the longer side of the mount.

The print with the greater margin (i.e. the ground not common to both prints) on the right should be marked " Right ", and that with the greater margin on the left should be marked " Left ". Also mark the top in each case. It may be said that there is no apparent top to a vertical aerial photograph, but the top in this case in intended to mean the uppermost side of the print when placed in its correct relative position, as previously described.

It is of the utmost importance that the prints should not be mixed, as, if the relative positions of the photographs are altered, hills become depressions, and vice versa.

Now select the portions of the photograph required for stereoscopic viewing. Cut the rectangles from each print, taking care that they correspond and that their base line is accurate. There is

some advantage if the prints are mounted so that the shadows are pointing to the bottom of the mount or slide.

The separation at which the prints should be mounted is from $2\frac{1}{2}$ in. to $2\frac{3}{4}$ in., i.e. any similar points on the two prints should be this distance apart. The relief is less exaggerated if the prints are mounted closer together.

Contact prints should be used if possible; soft, even prints, full of detail, give the best results; slight inequalities in definition or density are not of material consequence. It is, of course, desirable to select photographs with some prominent features in them, as they give more pleasing results from a stereoscopic point of view (fig. 18).

Section VI.—Filters: Their Object and Use in Aerial Photography

Light filters, when used in conjunction with panchromatic plates for aerial photography, are not primarily intended for colour correction purposes; that the colours are corrected by their use is purely incidental. With many of the uses to which filters are put in other classes of photography we are not concerned here. When taking photographs from the air, the special problem which presents itself is to find the best method of eliminating the effects of haze on the photographic plate, without at the same time unduly increasing the duration of the exposure. In taking photographs through this haze (or water-vapour in suspension), on a panchromatic plate, without a filter, the results invariably lack clearness, contrast, and definition. The sole cause of this is the chemical action of the specially active ultra-violet, violet, and blue rays, which are scattered to a greater extent by the haze than rays which are less chemically active.

All plates are more sensitive to the rays in the blue end of the spectrum. Therefore the effect on the plate is that the more active rays from the haze make a greater impression on the plate than the less active, i.e. the green, yellow, and red. It must also be remembered that the only image which the blue rays are conveying is a veil of fog.

Obviously, then, a means must be provided to restrain the action of the more chemically active rays, and allow the remainder to pass unchecked, thereby adjusting, as may be necessary, the actinic power of all the colours throughout the spectrum in their action on the plate.

PLATE XX

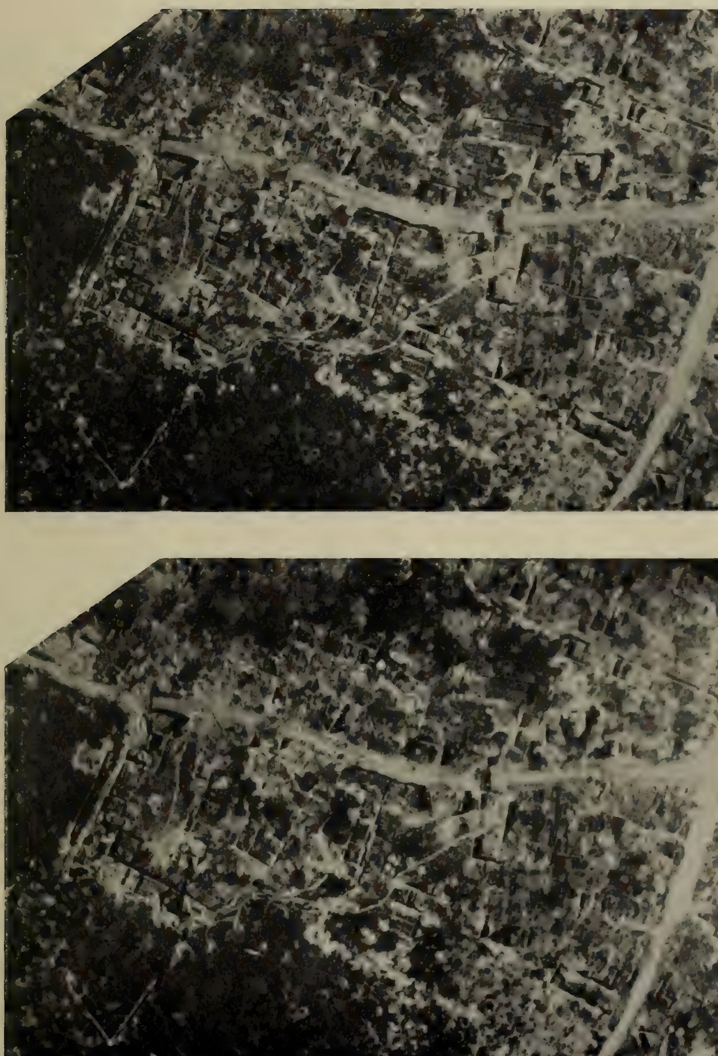

Fig. 18.—A Stereoscopic View of a French village near the British lines, 1917

Facing p. 424

This is generally accomplished by the use of a filter, which is also called a screen. These screens or filters prevent the violet rays from exerting undue influence upon the photographic plate; they weaken them, so to speak, in such a manner as to allow the other rays time to equalize their influence with the violet, but do not require too great an increase in the duration of the exposure. Filters with a multiplication factor of, say, 2 or 3 can be used, providing the absorption cut is correct. The most satisfactory filter is one in

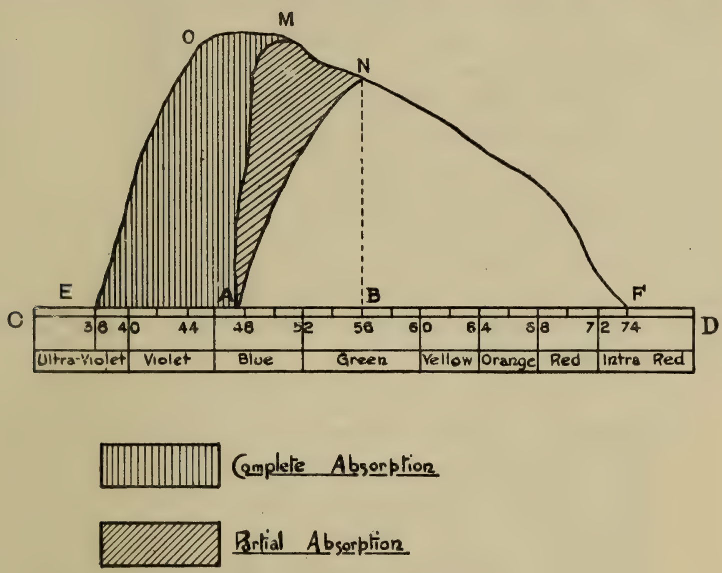

Fig. 19.—Diagram of Spectrum

which the absorption takes a sharp cut in the blue. The curve AMF shown in fig. 19 is a very suitable cut for aerial work.

This diagram also illustrates the necessity for the sharp cut. Let CD represent the spectrum, EOMNF the light value acting on a panchromatic plate without a filter; curve ANF is the light value when using a filter with a gradual cut; this clearly shows that the light between A and B is partially screened before reaching the plate.

In aerial photography, where exposures must be extremely fast, the value of obtaining the maximum of light is of first importance.

In selecting filters, the essential qualities are sharpness in cut and low multiplication factor. The filter may be made either of dyed gelatine, or dyed gelatine between optical flats. The former

is placed between the components of the lens, the latter fixed in front of the lens, either screwed in, or by the more simple method of clipping on by bayonet attachments.[1]

Section VII.—Taking of Aerial Photographs

The actual taking of aerial photographs does not present any great difficulties, since most of the cameras used are automatic in operation. The difficulty is to photograph the right point.

There are different classes of aerial photographs, requiring different methods for taking them, but at the very outset it must be made quite clear that the efficiency and skill of the pilot, combined with an efficient means of communication with his observer, are the governing factors in every case, whatever the type of the photographs may be—pin-points, overlaps, mosaics, or obliques.

Before the aeroplane is taken into the air for photographic work great care should be taken to see that everything required for the flight is in position and in good working order; it must be remembered that it is extremely difficult to make adjustments or to effect repairs when once in the air.

The following points are given in the sequence of operations:

(1) **Magazine or Slide Charging.**—This is of course a darkroom operation and requires great care, since it is done in total darkness when panchromatic plates are used. A finger-mark on the plate may cover the most important feature of a photograph. Badly cut plates should not be used; they frequently cause jams in the camera mechanism.
(2) Examine lens.
(3) Attach the driving and release gear.
(4) Set the shutter for the required exposure.
(5) Place the camera in position on its mounting.
(6) Adjust the mounting to the weight of the camera, and see that is it fixed in position with the optical axis vertical.

The operating of the camera in the air varies with the type in use. It would therefore be of no value to give details of any single camera.

Pin-point Photographs.—The class of photograph known as the "pin-point"—which is a single photograph of some point

[1] For further details on the subject of filters and colour sensitivity, see p. 204.

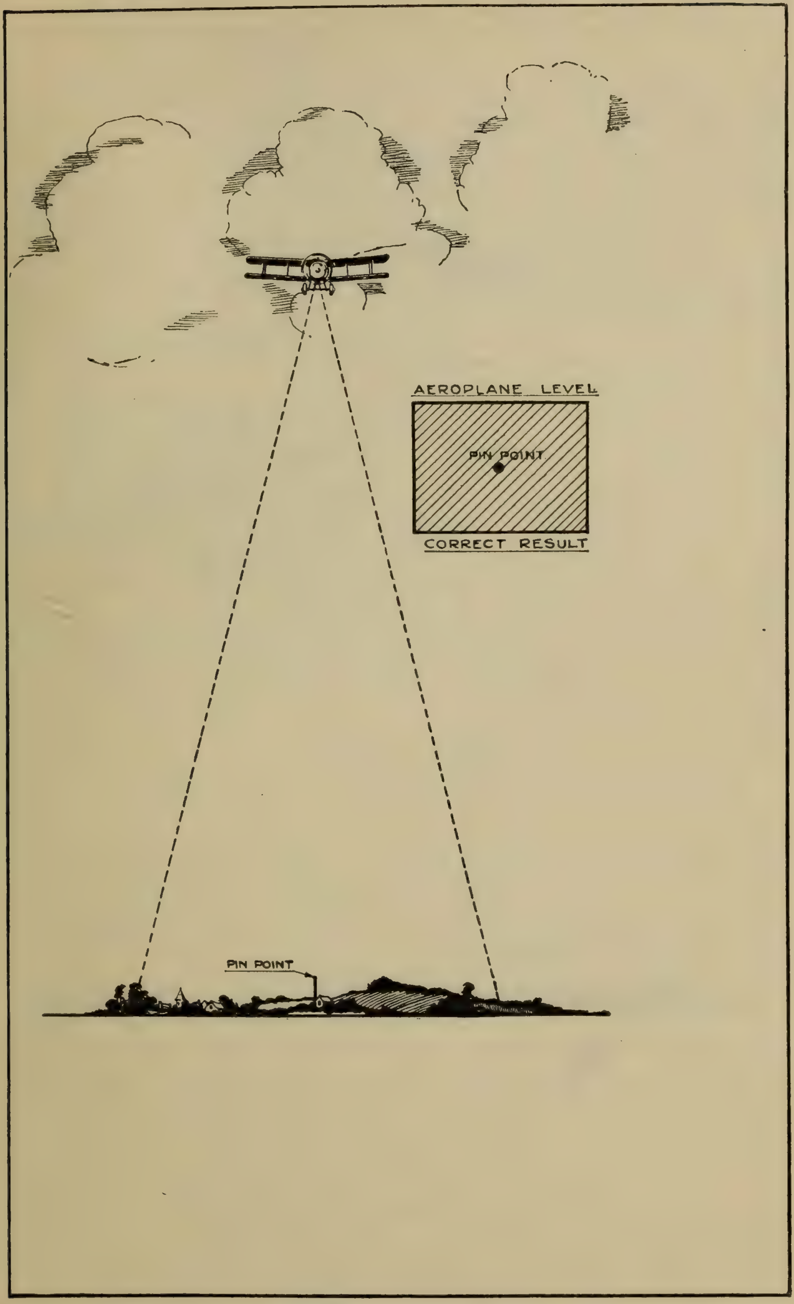

Fig. 20.—Aeroplane flying level

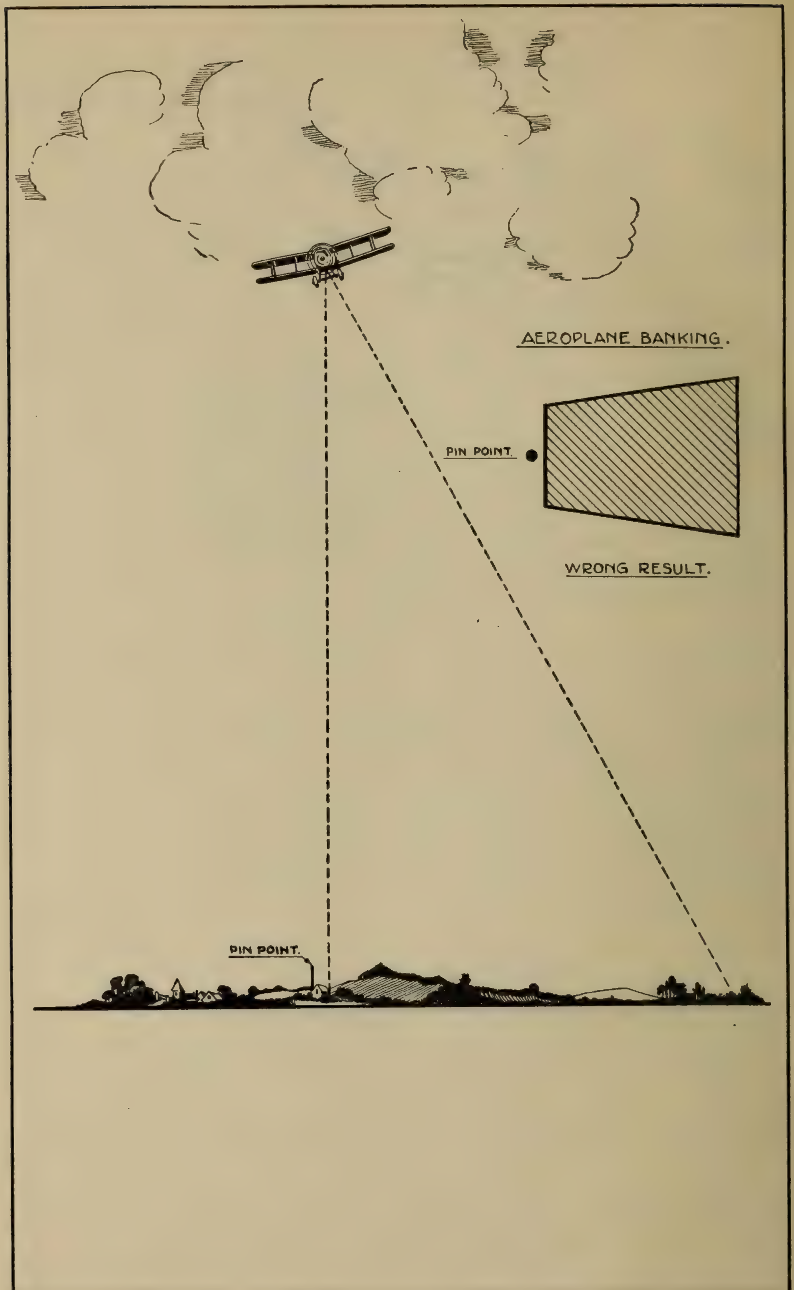

Fig. 21.—Aeroplane banking

shown on the map, such as cross roads, bridges, churches, &c.—is perhaps the most difficult to take.

When the height at which the exposure is to be made has been reached, the position of the camera should again be checked to ensure verticality. The sight must also be set in the same relative position. Since the optical axis of the lens is vertical, the importance of flying level when making exposures cannot be over-emphasized.

If the aircraft is either banking, diving, or climbing at the moment of exposure, it is possible that the pilot, when looking over the side of his machine, may see his objective directly beneath him; the lens

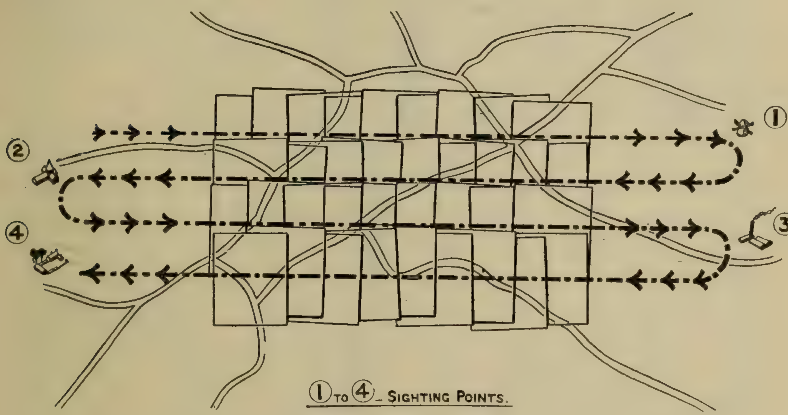

Fig. 22.—Diagram of Course of Aeroplane when taking Photographs for Mosaic

will, however, be pointing in an entirely different direction. Figs. 20 and 21 graphically explain errors likely to occur.

Overlaps.—These consist of a series of photographs overlapping each other in the line of flight. To ensure against gaps in these series, a 50-per-cent overlap is recommended. The application of these overlaps is chiefly for the making of plans for roads, rivers, canals, railways, &c.; they could also be used for photographing the coast-line and tidal rivers at high and low tides. Photographs would show the position and detail, whereas the maps could only give a general idea. The formula for the interval in seconds required between exposures is the same as that given on p. 423.

If a 50-per-cent overlap is given, it is possible to make stereographs of any position in the line of photographs. If possible, these series of photographs should be taken up or down wind. Cross winds tend to drift the machine, and cause gaps which are very diffi-

cult to fill in; in fact it is often more expedient to rephotograph a considerable portion of the line than to obtain one photograph which might, or might not, cover the gap. The method of overlapping is illustrated in figs. 22 and 23.

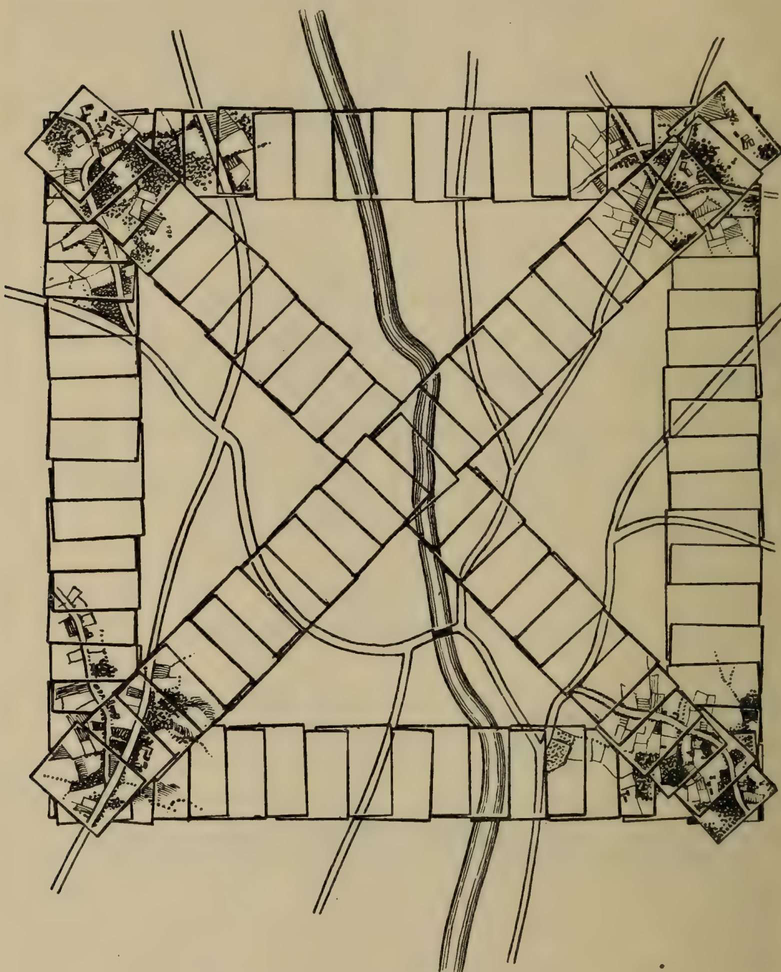

Fig. 23.—The Formation of a Skeleton Mosaic

Photo-mosaics.—This class varies considerably with the conditions and the type of country; for instance, a mosaic over country where good maps already exist, with an abundance of objects which could be used as sighting-points, presents little or no difficulty, but

in large open plains, forests, or desert lands it becomes a very difficult matter. Over country of the favourable type, a simple method is that of flying on sighting-points. This method, however, demands good weather and a clear atmosphere.

After working out the time interval between exposures, it is necessary to fix a series of sighting-points at the correct interval apart, then start the overlap or first line of photographs over one of these points, directing the course of the machine on to the second distant point. Having completed this first strip, turn well outside the area to be photographed, and re-enter it over the next point, then again fly straight on to the third distant point.

This operation should be continued until the whole area has been covered. An illustration of the method is shown in fig. 22. It is most essential, when taking photographs for mosaics, that the aircraft should be flown level, and that its height should remain constant; also, if drift is observed, the overlaps should be made flying to windward of the previous strip. Make all necessary observations and calculations on the ground. In country such as desert land, &c., where no maps are available and sighting-points are few (two conditions which are usually found together), a good method is to build up a skeleton mosaic bordering the area to be photographed, and then fly from corner to corner, thus providing a basis for operation. This skeleton, when complete, will provide not only a check on the accuracy of the subsequent mosaic, but also the sighting-points upon which to fly. (See fig. 23, an example of this method.)

A useful check on the accuracy of the overlaps or mosaics is to take oblique photographs from different view-points over the area to be covered. All points lying in a straight line on the obliques will be in a straight line on the ground, providing the latter is level.

Another check (in the case of an oblique which includes the horizon) is to draw a line passing through the optical centre of the photograph and cutting the horizon at right angles. All objects lying along the line on the photograph will be in a straight line on the ground, regardless of hills or undulations on the surface.

CHAPTER XI

Colour Photography

The subject of colour photography is so wide and deep, that in the space of a single chapter it is possible to deal with it only in outline, indicating some of the general principles underlying it, and their most successful application to practical methods.

From the earliest days of photography it was natural that people should dream of securing by its aid results in natural colours, particularly as it was noticed that untinted daguerreotypes sometimes showed faint traces of colour (especially in the flesh tones), probably due to the phenomenon known as interference. But so little progress was made towards this end, that in the first edition (1906) of *The Complete Photographer* Mr. R. Child Bayley confined his remarks on the subject to the three-colour process, which demanded the production of three separate negatives, and the subsequent combination of three positives made from them. He concluded: " Since the days of Daguerre and Talbot we have not apparently advanced one single step towards that goal—a simple and practical method of colour photography. But that is not to say that it is impossible, or improbable, or even far distant. At any moment it may leap into our knowledge, and we may be asking each other how it was that so simple a process was sought for in vain for so many years." In the very same year MM. Lumière took out their final British patent for the wonderful " autochrome " plate.

Although this was not the first form of " screen plate " it at once took rank as the best, and transparencies made by the screen-plate method still hold the field as the finest examples of colour photography. So far, these beautiful colour reproductions—produced entirely by mechanical means—have not been exploited to anything like the extent they deserve in the realms of commerce, science, art, medicine, &c. Yet they are incomparable for such purposes as the graphic representation of stained glass, flowers,

textiles, paintings, jewellery, pathological cases, geological and natural history objects, and so on. It has been said that the ideal colour photograph would be one approximating as closely as possible to the image on the focusing screen of the camera. If so, that ideal has been practically reached in the best screen-plate productions; but there would be many obvious advantages if the same result could as easily be obtained on a paper support. In this direction less progress has been made. When that goal also has been reached the use of direct colour photography will doubtless receive an enormous impetus.

The " discovery " of colour photography has been attributed to a French physicist—the late Professor Gabriel Lippmann—who, in 1891, stated that he had succeeded in obtaining direct in the camera a true colour image of the solar spectrum, and that the results were permanent. But there was no single discoverer of colour photography; and, as a matter of fact, modern methods are not an evolution of the process worked out by Lippmann, any more than monochrome photography is an evolution of Daguerre's process.

Lippmann's experiments involved an arrangement for exposing the plate while its thin chloride emulsion was in contact with a bath of mercury, which reflected back into the film the light rays reaching it. The " interference " of the direct and reflected rays produced " stationary " waves in the film, i.e. waves which rise and fall in the same spot without progressing. At the crests of the waves the light action was at its maximum, so that on development there were separate layers or strata of silver deposit, separated by a distance dependent on the wave-length of the particular colour ray. Viewed by transmitted light the result resembled an ordinary negative, but by various arrangements for viewing at the proper angle the reflected light from the laminæ in the emulsion reconstructed the colour rays which formed them. The process was ingenious, and interesting as a verification of certain theories of light and colour; but as a practical process it was far too cumbersome to come into general use. An example of a Lippmann heliochrome—the subject a stuffed parrot—may be seen in the museum of the Royal Photographic Society.

The colours due to interference, on which Lippmann based his process, are observed in the case of a bubble, mother of pearl, a film of mineral oil on the surface of water, and so on. But, as has been said, it was not on this phenomenon that the more successful processes of colour photography were founded. It was by the study

of the analysis and synthesis of light, and of the three-colour theory of colour vision, that further progress was made; and it is therefore necessary to know a few salient facts on these matters to understand the theory and evolution of practical colour photography.

If a pencil of white light is projected through a slit, and then through a triangular glass prism, it is found that the constituent rays of the white light are of different refrangibility, and emerge fan-wise so as to form on a plane white surface a multi-coloured ribbon or band—a spectrum. The hues are really infinite in number, but Newton named seven which he considered the most prominent and distinguishable—violet, indigo, blue, green, yellow, orange, red. Sometimes the indigo is omitted from the list, as many are unable to identify it as a distinct hue.

The spectrum band is really longer than it appears to the eye. Just as the ear is unable to distinguish sounds above or below certain pitches, so the eye is unable to recognize colour rays beyond the red (infra-red rays) at one extreme, or the violet (ultra-violet rays) at the other. But the normal eye can readily recognize either the whole of the seven colours named by Newton, or six of them. (For the present purpose only the solar or daylight spectrum need be considered.)

If the slit through which the light passes is sufficiently narrow it will be seen that the spectrum is crossed laterally by innumerable dark lines, each of which always appears in exactly the same position in the band. The more prominent of these were selected by Fraunhofer, and indicated by letters of the alphabet. Their position may be roughly shown thus:

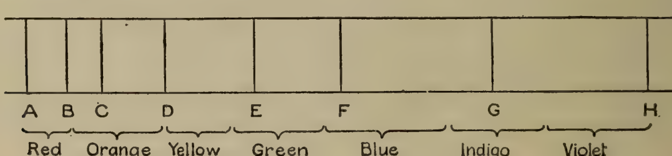

Fig. 1

Any particular hue of the spectrum can therefore be referred to by indicating its exact position in relation to the Fraunhofer lines. For example, " yellow-green " is a vague term; but D$\frac{1}{4}$E is definite and absolute, indicating the spectral colour seen one-quarter of the distance from the Fraunhofer line D towards E.

Any definite colour so selected is found to be associated with

ethereal vibrations—light waves—of a definite frequency and amplitude. If the waves are mentally visualized as a sinuous line it can be understood that the measurement of the wave is taken from the top of one crest to the top of the next, or from any one point in one wave to the corresponding point in the next. There are various units employed for this measurement. Angstrom used one ten-millionth part of a millimetre, which is thus known as the Angstrom Unit (A.U.). The wave-lengths which convey certain colour sensations to the eye may be roughly indicated thus:

Blue-violet, ...	4000 to 5000 A.U.;
Green, ...	5000 ,, 6000 A.U.;
Orange-red, ...	6000 ,, 7000 A.U.

These three visual colour sensations are of fundamental importance, as will appear shortly.

A mere glance at the spectrum shows a great variation in the luminosity of the colours as seen by the eye. The following table indicates, in the first column, the relative luminosity of some of the colours, and, in the second column, the light value of each, assuming the total light to be represented by 100.

Red	8	9·1
Orange	76	14·7
Yellow and yellow-green	100	39·6
Green and blue-green ..	64	30·3
Blue and indigo ..	12	3·8
Blue-violet	7	1·3
Violet	4	1·2

Also, the actinic value of the colour rays—their power to induce chemical action and change in the sensitive emulsion of an ordinary photographic plate—varies enormously. To obtain on an ordinary plate the same amount of density as would be given by white light, the relative exposures for lights of other colours would be, approximately: green, 4; yellow, 36; orange, 120; red, 1600.

This discrepancy between the effect of colour rays on the eye and on the ordinary plate was a great stumbling-block in working out any method of colour photography. Unless it had been counteracted the best methods now in use would have been impracticable.

The difficulty was overcome by two means. It was soon discovered that certain dyes rendered the emulsion of an ordinary plate more sensitive to yellow and green; and plates so treated for this purpose were generally known as ortho- or iso-chromatic. It was, of course, necessary to carry the sensitiveness still further, to include the red end of the spectrum as well; hence the panchromatic plate, which is the only kind of any use whatever in a photographic colour process. But even a panchromatic plate is disproportionately sensitive to the blue, violet, and ultra-violet rays—the very rays that are least luminous, or even invisible, to the eye. Therefore, in practice, a colour screen or filter is used, through which all light has to pass before reaching the plate. This filter is generally of a yellow colour, so that it cuts out or obstructs a certain proportion of the rays at the violet end of the spectrum, while allowing free passage to the visually brighter rays at the middle and towards the red.

Thus in all photographic colour processes the use of a panchromatic plate and a colour filter is imperative, in order that the results shall correspond to the original visual effect. It is not sufficient to use *any* filter and *any* plate in conjunction; the two must be carefully adjusted. All panchromatic plates have not the same degree of sensitiveness to certain parts of the spectrum, nor do all filters cut out the same rays. Only expert knowledge, derived from careful spectroscopic tests, can decide the exact tint and depth of filter to secure correct colour values in a particular panchromatic plate. It is also necessary to have filters of different character for each kind of artificial light, such as electric arc, filament lamps, incandescent gas, &c.

To return to the question of visual colour.

Thomas Young, in 1807, advanced the theory that in the retina there are three sets of nerve fibrils which can be so stimulated by light waves as to convey to the brain the three colour-sensations of red, green, and blue; or, as it is often put, orange-red, green, and blue-violet. As further research on this point was carried out by Von Helmholtz, it is generally known as the Young-Helmholtz theory. Clerk-Maxwell constructed curves to show how the spectral colours acted to create these three colour-sensations; and similar curves were laboriously worked out by Sir William Abney, whose results are roughly indicated in fig. 2.

The left-hand curve, rising slowly from the A line, reaching its maximum at about C$\frac{3}{4}$D, and sinking to F, indicates the parts of the spectrum giving the red sensation. The middle curve similarly

shows the creation of the green sensation, and the right-hand curve of the blue.

Any colour perception, then, is the result of these three primary sensations in various combinations and proportions, the number of which is infinite. This is the basis of colour photography. It will be noticed that in all the screen-plate processes the same three colour elements are employed—orange-red, green, blue-violet. In the screen itself these three colours are found, and these only. All the resulting hues and tints in the final result are due to the extent to which these three colours are allowed to take effect, as will be seen shortly.

The correspondence between this and our ordinary perception

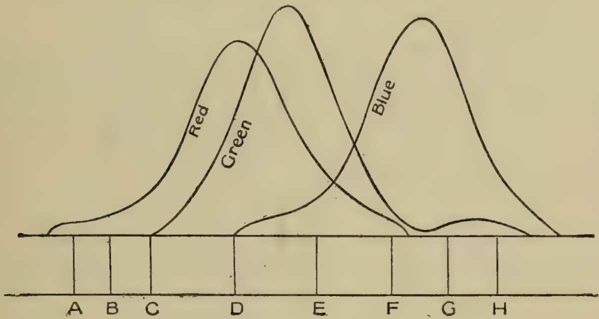

Fig. 2

of colour is exact. An orange, seen in daylight, has its characteristic colour because it absorbs or suppresses certain rays, and reflects to the eye only those particular rays which, in combination, create the sensation of orange colour. In a colour photograph of an orange we have taken steps which ensure that only those same rays reach the eye. A piece of ruby glass is red by transmitted light because it passes only those rays which collectively create that colour-sensation in the brain through the medium of the eye. The same colour in a photograph is produced by suppressing all but those same rays.

It may be well here to consider what happens when light is transmitted through coloured media on to a white screen, by means of a triple lantern such as that used by Mr. Frederick Ives. The three lenses were so arranged that they would project three discs side by side; but by a mechanical device it was possible to superpose either or both of the outer discs upon the middle one. Each lens was fitted with a bright-coloured glass, the respective colours being

roughly indicated as red, green, and blue. These brilliant discs were projected side by side, and then superposed. The resulting single disc was, within a little, white.

At first blush it seems impossible to produce a white disc when no white light whatever is reaching the screen, but when all the rays are passing through either a red, a green, or a blue glass. But the explanation is simple. We may imagine the complete bundle of rays constituting white light divided into three smaller bundles, the first of which contains all the rays giving rise to the red sensation, the second all those creating the green sensation, and the third all those that produce the blue sensation. It is obvious that when these three bundles of rays are projected on to the same area they collectively contribute the total rays of the original bundle, and thus reconstruct white light.

If the light from each of the three lenses could be completely obstructed it would be possible to produce the following effects, according to the coloured lights projected.

R	G	B	White.
R			Red.
R		B	Purple.
R	G		Yellow.
	G		Green.
	G	B	Blue-green.
		B	Blue.
	(Nil)		Black.

Instead of the colours being completely obscured they could be partially cut off, or damped down, by interposing such varied gradations of density as are seen in a negative, and by this means all other hues and tints could be produced.

This is the trichromatic method adopted by Mr. F. E. Ives, of Philadelphia. He made three separate negatives of the subject through three colour-filters—say red, green, and blue—corresponding to the three colour-sensations as plotted in Clerk-Maxwell's curves. As a rule, these negatives were taken successively, side by side, on one plate; but special cameras have been devised fitted with mirrors in such a way that the image is simultaneously received on three different plates or films. The former plan involves three separate exposures, the length varying according to the colour of the filter; the single-exposure apparatus is expensive, and by no means easy to use.

The negative made through the red filter gave gradations corresponding with the degree to which the objects photographed reflected rays included in the Clerk-Maxwell red sensation. A transparency from this negative behind the lantern lens with the red glass would therefore give on the screen the correct values of the red elements of the subject. A similar result would follow with the transparencies from the green and the blue sensation negatives. The result when the three images were superposed was a picture in true natural colours and light and shade.

A further step towards realism was made when Ives produced similar trichromatic transparencies in stereoscopic form, and invented an instrument called the Krōmskōp, by which the results could be viewed as easily as in an ordinary stereoscope. The effects were often strikingly beautiful and correct in colour; but there remained the drawback of the difficult character of a process which necessitated the use of special apparatus for taking and viewing, and the production of three negatives and three transparencies each correct in its density and gradations.

A process also dependent on the making of three negatives was developed by Mr. E. Sanger-Shepherd; but in this case it was possible to produce a single colour transparency for projection by the ordinary lantern. Some description of this process is necessary; first, because it gives excellent results, and secondly because a new point in colour rendering arises.

When the three negatives are finished, the first step is to make a black-tone lantern slide from the red-filter negative, and by means of a special solution the black image is changed to greenish-blue.

Two positives are then made by printing simultaneously from the green and the blue-violet filter negatives. These positives are made on a special celluloid film, coated with gelatine containing silver bromide, and sensitized with a solution of potassium bichromate. Exposure is made through the celluloid, and the visible image resembles that of a platinum print before development, or of a print in bichromated gelatine for the oil-printing process. Immersion in warm water dissolves away the unexposed portions of the gelatine, leaving a positive image in white. Fixing in hyposulphite of soda removes the bromide of silver, and leaves a colourless gelatine relief. The two positives are then washed, and are ready for staining. For this purpose they are cut apart. The positive from the green-filter negative is dyed pink, and that from the blue-violet negative yellow. When the stained films are dry they are superposed on the greenish-

blue lantern slide, and bound up with a mask and cover-glass as in the case of an ordinary slide. An improvement is effected by using Canada balsam to cement the films in optical contact.

The new point that here emerges concerns the colours of the positive images. In the Ives triple projection the colour of each positive corresponded roughly with the colour of the filter through which its negative was made; in the Sanger-Shepherd process the colour of each positive is *complementary* to the filter colour of its negative. The reason for this needs explanation.

In the Ives process coloured light is added to coloured light, so that, as has been explained, the total rays constituting white light are contributed. If instead of three lenses one only were used, and the light projected into the three colour screens superposed, none would emerge. The rays not stopped by one coloured glass would be stopped by another. Similarly, if red, green, and blue pigments were applied one over the other, the result would approximate to black. In the former case the screens are each contributing certain colour rays—the *additive* method; in the latter they are each obstructing certain rays—the *subtractive* method.

Consider the case of a negative made through the red filter. The denser parts of the negative represent the action of the red rays that have reached the plate; therefore a transparency from this negative records the red effect by its clearer parts. Consequently, if light passing through the clearer parts also passes through a red glass the proper red effect will be projected on to the screen. But if from the same negative an " image " in gelatine is made (as in the Sanger-Shepherd process), this image is made through the clearer parts of the negative—the parts that have *not* recorded red rays—and it must therefore be stained to the complementary greenish-blue.

The point is further illustrated in the methods of making a three-colour print by the imbibition and transference of dyes, which Sanger-Shepherd and others have adopted. From the three negatives positives are made in transparent gelatine as just described. That from the green-filter negative is placed in a pink dye, which it absorbs in proportion to the thickness and distribution of the gelatine. It is then squeezed down on to a sheet of wet gelatinized paper, which, in a few minutes, absorbs the whole of the pink dye. The image from the blue-filter negative is stained yellow, adjusted in exact register on the pink image, and left till this dye has also been absorbed. Finally, the red-filter negative record is dyed blue, and its colour transferred to the pink-and-yellow image.

Other colour prints are obtained on somewhat similar lines by superimposing stripping films of carbon tissue; by the use of the gum-bichromate process; or by means of the bromide prints and "colour sheets" of the Raydex process. In addition to the great care and accuracy required for the production of colour prints on paper, there is the drawback that the results are often dull, and lacking in brilliance and transparency, largely due to the fact that the light has to penetrate the pigments or dyes and be reflected from the paper. A great proportion is naturally absorbed, and attempts to increase brilliance by resorting to such devices as supports with bright metallic surfaces have not been a success. From time to time a few notably good and promising colour prints on paper have been produced, and they possess one great advantage in the character of the image, which is of "photographic" quality, and has none of the grain or pattern inseparable from the screen-plate processes. But it may safely be said that no method of colour photography on paper has yet been evolved which makes it easy to turn out numbers of duplicate prints, fairly uniform in general character and correct in colour. It is to screen-plate transparencies that we must turn for the best colour results so far achieved.

Before examining some of the methods by which these are produced, it may be well to re-state certain facts in colour vision, so that it may ultimately be quite clear how such a colour transparency achieves its purpose. This knowledge is of assistance in practical work, as it leads to perception of faults, suggests remedies, and paves the way to the attainment of still better methods of greater commercial value. For if a screen-plate transparency is perfect it will reproduce the subject with every hue and shade, with high lights, half-tones, and shadows, by means of light transmitted through three colour elements and modified by the presence of a positive photographic image in metallic silver.

The three sets of nerve fibrils in the retina of the eye are respectively stimulated by the composite colours, red, green, and blue, as shown in the colour sensation curves of Abney and others. Thus, simultaneous affection of the fibrils sensitive to red and to green gives, according to the ratio between the affections, any spectrum colour from red, through orange and yellow, to green; affection of the green and the violet sensitive fibrils gives also the intermediate blues. Affection of all three may give some particular tint, or, in certain properly adjusted proportions, white.

The particular hue determines colour; its purity depends on

the absence of admixture with white light; its luminosity regulates the shade or tone. Thus, if we take a definite spectrum red light, and reduce its purity by admixtures with white light, it becomes light red, pink, or pinkish white; if we reduce its luminosity by admixture with black we produce colours through terra-cotta to brown; if we reduce both its purity and luminosity by admixture with various shades of grey, we secure russet brown, maroon, and so on. Similarly with other colours.

Black is negation of colour—no light sensation at all; grey is white rendered deficient in luminosity through admixture of black. The blacks and greys are obtained by the gradations of the photographic positive.

The well-known autochrome plate is made by MM. Lumière, of Lyons, and a somewhat detailed consideration of it will illustrate the working of other screen plates.

Grains of potato starch, uniform in size, are dyed orange-red, green, and blue-violet, and intimately mixed in the ratio of 3, 4, and 2. They are so minute that it is estimated that there are approximately 200 millions on a half-plate ($6\frac{1}{2} \times 4\frac{3}{4}$ in.). These dyed grains are sifted on to a glass plate with a tacky surface, and rolled flat. This is done in such a way that there is practically no overlapping, and very little "clumping" together of a considerable number of grains of the same colour. Any minute interstices are filled with black pigment. The mosaic of starch grains is varnished and then coated with a panchromatic emulsion.

The plate is exposed through the glass (which must be perfectly clean), so that all the light that reaches the sensitive film passes first through the screen of starch grains. This necessitates placing the plate in the dark slide the reverse way to that for ordinary exposures, and a black card is used to protect the film from the springs on the septum of the slide. It also necessitates the reversal of the ground glass of the focusing screen.

A special light-filter, adjusted to the plate, must be used. This slightly displaces the focal plane. If it is placed behind the lens the displacement is about equal to that caused by reversing the plate, so that in this position no allowance need be made with cameras of fixed focus, or which focus by scale. With visual focusing on a screen it is immaterial whether the filter is behind or in front of the lens.

The speed of the plate, allowing for the starch-grain screen and the light-filter, is H. and D., 2; Watkins, 3; Wynne, *f*/14. These

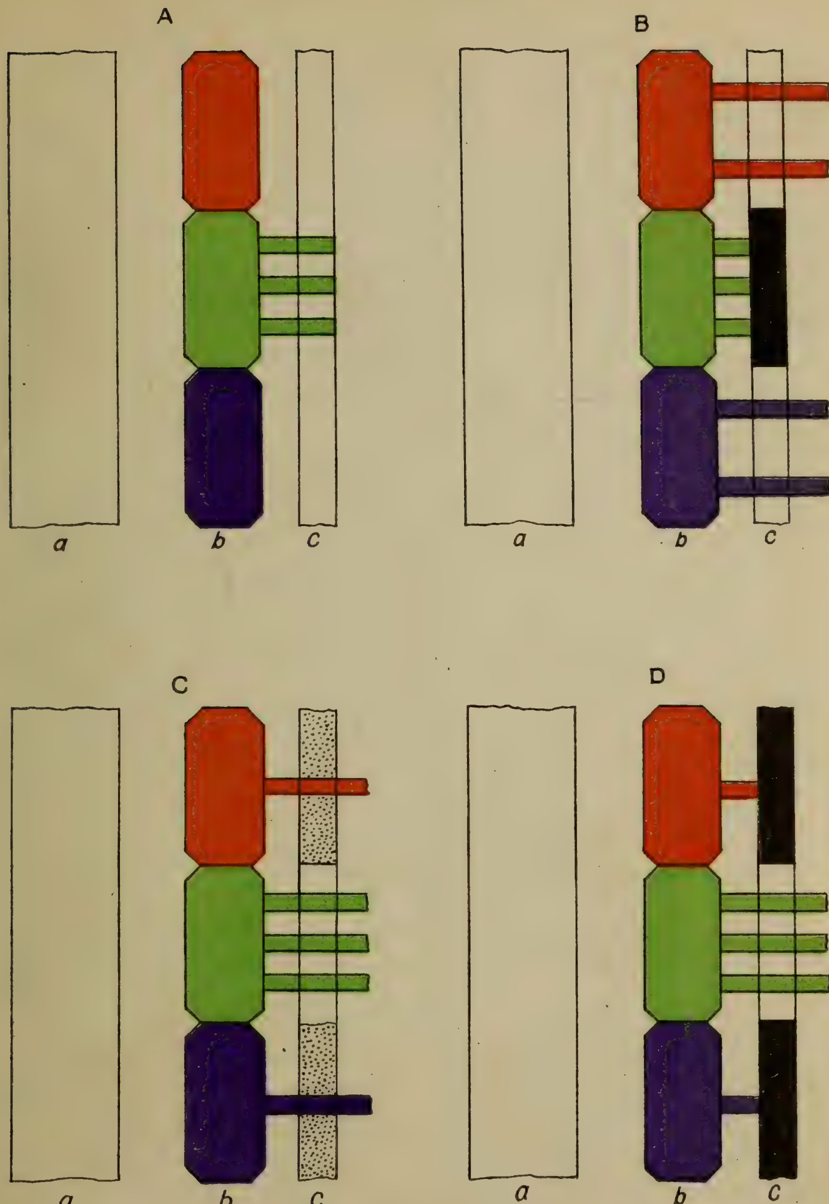

Fig. 3.—Colour Production with Autochrome Plate

(Conventional diagrams showing production of single colour corresponding to that of one of the three starch-grain elements.)

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speeds are nominal rather than actual, as they vary according to the character of the light; so that although the use of an exposure meter is of great assistance a certain amount of practical experience is required.

The exposed plate may be developed in many ways, preferably with a standard solution of quinomet, in complete darkness or with a special safe-light, by observation, or the time-and-temperature method. The result is of course a negative image, and the subject appears, as will be explained presently, in complementary colours.

The negative silver image is next completely dissolved away in an acid-permanganate bath, and the plate re-developed in daylight. This second development demands a reagent that will give an image in pure black and greys; the original quinomet solution is suitable. The result is a positive image composed of the silver unused in the negative, and the true colours now appear. It may or may not be necessary to intensify this image. If it is, the plate must afterwards be fixed in a hypo solution. In either case it is quickly washed, dried, and varnished. Some autochrome workers manage, as a rule, to avoid the necessity for intensification. They give a very full exposure, and stop development at a stage where the image is still thin, but complete in detail and gradation. This leaves sufficient unaltered silver to give a strong image on second development without having to reinforce it.

It may now be helpful to illustrate the various stages by means of a modification of some diagrams (fig. 3) used for the purpose by Mr. E. A. Salt. In each case *a* represents (in section) the glass, *b* three starch grains (orange-red, green, and blue-violet), *c* the panchromatic film. The light is travelling from the left, first passing through the lens and filter. The object being photographed is supposed to be an evenly illuminated plane surface of exactly the same colour as the green starch grain.

A shows that the only light reaching the sensitive film is that passing through the green grain. B indicates the condition after development; there is a patch of opacity behind the green grain. When examined by transmitted light there is no sign of green, but rays are passing through both red and blue. This gives, in combination, " minus-green ", i.e. the colour given by white light minus its green rays. As the rays are weakened by the unaltered emulsion two emerging rays instead of three are shown. In C, the negative image has been reversed. The metallic silver behind the green grain is dissolved, and the green rays pass through the clear gelatine.

But the deposit behind the red and blue grains is not sufficiently dense, and is allowing some light to pass, as suggested by a single ray. This not only alters the character of the green but weakens it, as the condition is approximating to that of *all* the rays passing, and so giving white light. Intensification gives the result shown in D. The red and blue rays are now completely obstructed by the dense silver deposit, and the green rays alone pass, giving the exact colour of the object.

If the green object had had gradations of light and shade they would have been indicated by the positive image. Instead of every green grain being backed by clear gelatine, some only would have been clear, others more or less obstructed by a deposit of silver. Had the object not been the exact green of the starch grain the colour of the final result would have been modified by the passage of an appropriate admixture of rays passing through either the red, or the blue, or both. Similarly with all other colours and shades. They would all be obtained according to the extent to which the gradations of the positive image allowed the light to pass through this grain or that. It is obvious that no " registration " of the positive image with the screen is required. Each grain controls the character of the image behind it.

A curious fact was early noticed about the autochrome plate—the rendering of a pure white, such as the high light on a linen collar. This could not be accounted for by the mere passage of unobstructed light through all the starch grains, as the screen of the plate, as in all screen plates, is not entirely colourless. Dr. G. Lindsay Johnson no doubt arrived at the correct solution when he discovered that in such parts the film showed large numbers of silver particles, and that the effect of these was so to " scatter " the light that any suggestion of colour was entirely removed.

An objection often raised against the autochrome plate is that there can be no duplication of a result except by exposing more than one plate on the subject; that one exposure means one colour transparency, and there an end. This is quite wrong. From a successful result it is quite possible to make any number of replicas by copying on other autochrome plates, either by daylight or by an apparatus employing magnesium ribbon as the illuminant. It is also feasible to fix a plate after first development, and so retain a negative from which positives can be made direct. As a matter of fact many of the finest specimens shown by MM. Lumière and others are not originals but copies.

One of the simplest of screen plates, as far as structure is concerned, was that introduced by Professor Joly, of Dublin, about 1894. He prepared a screen ruled with contiguous parallel lines, about 150 to the inch, in sequence of orange, blue-green, and blue. A panchromatic plate was exposed with its film in contact with the screen. From the negative a positive was made, and this was bound up with an identically ruled screen in red, green, and blue-violet. The colour effects were obtained in exactly the same way as has been diagrammatically illustrated in the case of the autochrome. J. W. M'Donough used a similar method, ruling as many as 420 coloured lines to the inch.

But a finely ruled plate sets up diffraction. Very pure and perfect spectra can be produced by passing light through such a screen, one characteristic of such spectra being that the colour bands are properly distributed in proportion to wave-lengths, and not crowded together at the red end, and spread out at the violet end, as when a prism is employed. Consequently the colours given by a ruled screen plate of this type are often seriously impaired by the production of a number of weak and confused spectra.

The Thames plate was patented by C. L. Finlay in 1906. It had a pattern of adjacent circles in red and green, with blue interspaces. From this was evolved the popular Paget screen plate, with a mosaic of coloured squares, about 300 to the linear inch, instead of circles. This could be used either by coating the emulsion on the screen, as in the autochrome; or by using a separate transparency and screen, as in the Joly process. The latter method has established itself in popular favour.

The taking screen and the viewing screen are identical in pattern, square for square, but the colours are slightly different, so that the two are not interchangeable. Taking into account the light filter and the colour screen the panchromatic plate used has a speed of about Watkins, 15; Wynne, *f*/24; which is considerably faster than the autochrome. Indeed, with suitable light and subject successful hand-camera exposures have been made on the plates.

The plate is exposed with its film in close and complete contact with the taking screen, and a negative is obtained from which ordinary prints, enlargements, or lantern slides can be made without the screen pattern being unpleasantly apparent. For colour results a positive transparency is made from the negative, and bound up in exact register with a viewing screen. It is clear that the number of duplicates is limited only by the number of transparencies and

screens employed. The *rationale* of the production of colour by this means is precisely analogous to that explained in the case of the autochrome plate.

A successful Paget lantern slide is not only very good in colour, but particularly transparent; so that it can be shown in conjunction with monochrome slides without any special arrangements for projection.

A Paget transparency demands not only that the positive shall be accurately in register, dot for dot, with the viewing screen, but that means must be taken to secure their remaining in register. If they are merely bound together with gummed strips even a slight lateral strain may throw them out of register, and the colours are at once lost. From long experience the writer recommends a special "dodge" for securing and preserving perfect register.

At each corner of the transparency is placed a spot of seccotine, or fish glue, about the size of a small pin's head. The viewing screen is laid on the transparency, and the two held up to a good light. The seccotine spreads under pressure into small patches, and these act as a sort of lubricant which enables the screen to be moved easily in any direction. Generally the first effect seen is that of a small-patterned plaid. As the screen is moved this enlarges and diffuses until at a certain stage it disappears, and each colour element in the screen finds its corresponding dot in the positive. The slide should be slightly turned at an angle in all four directions to see if the colours can be improved, and if so the screen should be gently forced in that direction by a sort of lateral squeeze. When the colours are at their best with the line of sight at exact right angles with the plane of the glass, the two plates are held together by a couple of bulldog clips, and set aside for some hours. The seccotine then hardens so that the two glasses are permanently fixed in register.

It is not possible to use paper masks in this case, as they would cause a slight separation between positive and screen, which is fatal. The best plan is to rule marginal lines on the transparency with photopake, or similar pigment, and fill in the margins by means of a brush.

There is one drawback to the use of a separate screen and transparency, and that is the trouble caused by parallax. For the present purpose this may be defined as the displacement of one object in relation to another by an alteration in the line of sight. Unless we look perpendicularly through a given dot on the screen we do not see what is behind it, but what is beside it.

This may be illustrated by an exaggerated diagram (fig. 4). The upper squares represent two patches of density and one of clear glass in the positive, and these are supposed to be in contact with three colour elements, R, G, and B—red, green, and blue. If light reaches the eye in the direction of the arrow *a* it passes through the clear glass and illuminates the green spot; but if it travels in the direction of the arrows *b* and *c* it will illuminate the blue or the red.

This effect is at once apparent when a transparency by such a "separate" method as the Paget is viewed at an angle. The colours are at once falsified. It is obviously impossible that the line of sight, when viewing direct, shall be even approximately perpendicular to the plate over any considerable area, so that to some extent the practicable size of a "separate" transparency is limited. The same difficulty does not arise in the "combined" method, where the emulsion is in optical contact with the screen.

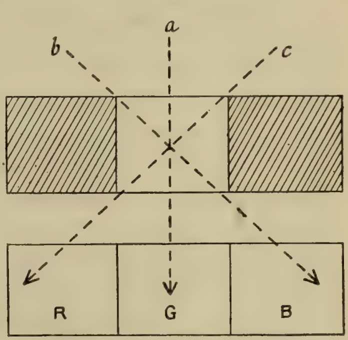


Fig. 4

In a separate method, like the Paget, the development of the negative is exactly the same as in the case of a panchromatic plate for monochrome work, except that it is not carried quite so far as usual. It is therefore an advantage to use desensitol. This is a concentrated solution which, suitably diluted, is used as a bath for immersion of the plate before development, a couple of minutes being sufficient to make even a rapid panchromatic plate proof against fogging by a reasonable exposure to a light which would otherwise fog it hopelessly. Examination of the progress of development is thus rendered possible. The resulting stain disappears after the application of an acid fixing bath and subsequent washing. Desensitol cannot so safely be used for the autochrome plate, as prolonged washing at any stage is neither necessary nor desirable.

There have been various other screen-plate methods, differing according to the pattern of the screen, and the adoption of the combined or separate methods; but practically the only survivors appealing to the general practitioner in photography are the autochrome and the Paget. Each has its advantages; both are excellent. Detailed working instructions have not been given here, as they are supplied

with every packet of plates. The user would be well advised to follow rigidly and precisely one of the methods of manipulation laid down, and only to depart from it when practice and experience suggest some modification of the procedure. For the perfection and correct adjustment of the screen, the filter, and the emulsion he is dependent on the makers; the successful carrying out of the operations involved depends on his own care, skill, and judgment. He should aim at technical perfection, which in this case implies the accurate recording of every colour, shade, and detail of his subject. As far as perfection is humanly attainable both the plates named are capable of achieving it.

In full working instructions attention is generally drawn to the faults and defects most likely to arise, together with their causes and remedies. There are, however, one or two points to which special attention may be drawn, as they are frequently overlooked. First, no light must reach the plate unless it has passed through the colour filter. A very small amount of unscreened light is sufficient to cause a general blue or violet tinge over the whole subject. Secondly, it is strongly advisable to use a lens hood, so that as far as possible the only light entering the camera is that actually required for forming the image. A patch of strong coloured light on the bellows near the plate may be partially reflected on to it. Thirdly, before an exposure is made the subject should be critically examined to see if there is obvious reflection of colour from objects outside the field of view, so that it may be screened off.

As was hinted early in this section, the commercial value and possibilities of the rendering of subjects in colour by means of these screen plates have as yet been barely recognized. There is no other method by which can be obtained reproductions that are at once so accurate and beautiful, so simple and cheap. But probably full recognition will come in the near future as more colour photography is undertaken, and the results become better known.

Colour plates may be exposed by flashlight, and for both the autochrome and the Paget plate special filters of a greenish-yellow colour are supplied. A modified form of flash-powder is recommended by MM. Lumière and Seyewetz, perchlorate of potassium being substituted for the usual chlorate. The light produced is richer in actinic rays, and the mixture is safer in use. The powder is prepared by taking 2 parts of finely sifted magnesium powder, and 1 part potassium perchlorate, and mixing thoroughly with a feather or a piece of card. The amount required depends on the distance

of the objects photographed, the use or otherwise of a diffusing screen, and very largely on the size of the room and the colour of the walls. The last-named consideration has a special importance in colour work, as the reflected light may impart a general tint to the plate.

The point also arises that colour results, to be seen at their best, should as a general rule be viewed in the same kind of light as that by which they were obtained. The great majority of colour plates are exposed by daylight, and if examined by any form of artificial light often suffer seriously as far as many of the colours are concerned. Artificial light can be made to approximate almost exactly to daylight, but the necessary equipment is not generally available. Many workers attempt to modify their colour transparencies by the use of weak dyes, either applied to the gelatine, or on a separate film (much in the same way as a water-colour painter will wash colour over the whole drawing); but such a procedure needs great care and judgment, or it is apt to do more harm than good.

Increasing attention is being paid to the production of stereoscopic transparencies by the autochrome process, especially in the popular French size of plate, 45 × 107 mm. Many of the cameras for this size are fitted, as a matter of course, with the necessary colour filters, and the slides are made suitable for carrying autochrome plates. The small size is an important factor as far as cost is concerned. Even when viewed through the lenses of the stereoscope the grain of the plate is by no means obtrusive, although the high lights and lighter tones often show a sort of iridescence. Nor, curiously enough, does the small size of the pictures detract from their effectiveness. Minute patches of colour are correctly rendered, and the illusion of natural size, space, distance, and atmosphere is remarkable. It is advisable in this, as in other forms of stereoscopic work, to keep the transparencies on the soft and delicate side. It is, of course, necessary to cut the plate through the middle with a diamond so that the pictures may be transposed when mounted for viewing. To prevent damage to the film in cutting, two cuts should be made, close together, and right down to the glass, with a sharp penknife, and the diamond cut on the glass side made between them.

Another branch of work in which colour photography plays an important part is photomicrography, but this is a task for the enthusiastic specialist rather than the average photographer. In many cases, especially where only low magnifications are concerned, a direct autochrome exposure gives quite satisfactory results; and where fairly large areas of about the same colour are present the

Paget plate will also do excellent service. Such work is comparatively simple and straightforward. But in perhaps the majority of cases any grain or structure in the screen, however fine, is a serious drawback, especially when the slides are intended for optical projection rather than for direct examination. It is therefore necessary to resort to such a process as the Sanger-Shepherd triple colour, where the images are of photographic quality and practically grainless.

This, as has already been explained, demands the production of three negatives, taken through filters which in this case must be accurately adjusted to the particular form of illuminant used; and the subsequent production and perfect superposition of three positives appropriately stained or toned. Obviously the work is particularly exacting when microscopic subjects, with their small scale, fine detail, and critical definition, are concerned. The whole subject is far too vast and complicated to deal with in small space. The only course for the photographer who takes up this difficult work is first of all to decide on the particular process that seems best fitted to his own type of subjects, obtain all the working instructions bearing upon it, and arrive at more complete data by means of careful experiments, the results of each being noted, and variations and modifications made accordingly. The microscopist who can already produce successful monochrome photographs of his subjects should find no great additional difficulties in passing on to colour work, especially if it is of such a nature that a screen plate answers the purpose desired.

It is worthy of consideration, in the writer's opinion, whether it would not be possible for all-round photomicrographic work to devise a non-screen two-colour process such as has been adopted with considerable success for other forms of work. The Eastman Kodachrome process may be suggested as a good type.

A process of this kind would follow some such lines as these. Two panchromatic plates are exposed successively, one through a red filter and the other through a green, the colours of the filters being adjusted both to plate and illuminant. As the subject is stationary, and the illuminant remains constant, there is no difficulty about making the two exposures. The plates are developed, fixed, washed, and dried. From these negatives duplicate negatives are made on thin celluloid film. In this case the silver image is bleached, and the film fixed, washed, and dried, showing then no sign of an image. The negative film made through the red filter is then immersed in a bath of green dye, and the green-filter negative in a

bath of red dye; and, after drying, the two colour images are bound together in correct register between cover-glasses. The substitution of films for the original glass plates is necessary in order to get the most perfect coincidence of image possible, the diffusion caused by the thickness of one of the glasses not being permissible for this class of work. This is merely a brief indication of a routine which should be quite practicable, as with small variations it has already been successfully employed.

Somewhere about 1825 Sir John Herschel pointed out that if a coin were spun on edge at a certain rate, both sides were seen at the same time. Dr. Fitton at once repeated the experiment by printing a cage on one side of a cardboard disc and a bird on the other, so that when the disc was rapidly revolved by means of strings attached to opposite edges, the bird appeared in the cage. By 1882 Mr. Muybridge, of Kingston-on-Thames, was exhibiting in London " moving pictures " of a sort. These he obtained by taking photographs with a series of cameras placed in line at regular intervals, their shutters being electrically operated by the persons or animals moving in front of them. These serial photographs were projected on to a screen by an apparatus resembling the Zoëtrope, or " wheel of life ", and conveyed the idea of continuous motion by reason of the " persistence of vision " illustrated by Herschel.

The introduction of long flexible strips of sensitized celluloid film in 1888 set many experimentalists to work at producing serial photographs at shorter intervals, and spread over longer periods; and the efforts of Messrs. Birt Acres, W. Friese-Greene, Edison, Lumière, and many others resulted in strikingly successful results in kinematographic projection by 1895.

It was then inevitable that knowledge of such colour-producing methods as that of Ives should suggest to inventors their application to the kinematograph. The first attempts to take the pictures in triple series through red, green, and blue filters were unsuccessful; the predominance of the blue rays overpowered the reds and greens, and the resulting colours were weak and unbalanced. Moreover, there was the necessity of running both the taking and projecting machines at three times the normal rate, with the consequent risk of under-exposure, and the use of three times the length of film to record the same amount of subject.

Yet, much less than a century after Herschel's spun coin, colour-kinematography was an accomplished fact. Messrs. Charles Urban and G. Albert Smith devised a method known as kinemacolor,

reducing the series to two pictures for the complete colour sensation. In their revolving colour filter a skeleton wheel has four segments, two of which are open. The third is filled with green-stained gelatine, which also passes a certain amount of blue light. The fourth is filled with a red filter, the middle portion of which has superposed a segment of green, carefully adjusted in size so as to damp down the vivid red rays to such an extent that the revolving filter gives on the screen the nearest possible approach to white light. Without the green adjusting segment there would be a distinctly red tinge.

To permit of the standard rate of projection of sixteen pictures per second the apparatus, both in taking and projecting, must run at twice the normal rate, as sixteen *pairs* of pictures are required. Of each pair, one is taken through a red filter, the other through a green. The positives obtained from these negatives are of the usual monochrome character, containing no colour in themselves. The colour results from their being projected through colour filters similar to those through which the negatives were taken.

In exposing the film the section taken behind the red filter will be affected only by the red group of rays. The positive from this section will record the amount and distribution of these red rays by its less clear, or perhaps quite clear, parts. When this positive is in the gate of the projecting lantern the red segment of the revolving filter will be in position, and the proper proportion of the red group of rays will be projected on to the screen. This is immediately followed by the green-sensation positive and the green colour-filter, and the rapidity of the successive projections will result in an apparently simultaneous blending of the two groups of colour rays.

The drawback of the double rate of speed required for the kinemacolor process has been mentioned, and apart from this there are certain imperfections. Fringes of colour are apt to appear, especially where light comes against dark; some of the more delicate and subtle colours may be entirely missing; other colours may be too strong and crude. But in comparing the merits and demerits of similar processes, it is advisable to take each at its best, and so judge what are its highest possibilities; and, so considered, the kinemacolor process is of high merit and value.

Of other systems of colour-kinematography the Prizma film process is the most remarkable. It has been patented quite recently by Mr. W. D. Van Dorn Kelley. The extraordinary nature of his achievement will be realized when it is stated that a single unit of

Prizma film, when held in the hand and examined by transmitted light, embodies in itself the complete colour of the subject. It follows that Prizma films may be projected in the ordinary way, with any standard machine, at the usual rate of speed, and without any colour screens. Further, the results are remarkably good in every way.

The Prizma process is intricate and complicated, and there are several alternative methods of arriving at the same final result. It would therefore be impossible, without long and detailed description and the aid of coloured diagrams, to make the process quite clear and easily comprehensible. At the same time it is so ingenious, and such a marvel of mechanical and technical accuracy, that a modified summary of the process as described in the *British Journal of Photography* will be of interest to those who care to think out the details, the general lines of which should be quite intelligible to all who have grasped some of the fundamental principles of colour laid down in this section.

The negative film consists of successive pairs of identical images (as far as subject is concerned), one picture of each pair being made through a red-orange screen and the other through a complementary blue-green screen.

The positive film has a sensitive emulsion on *both* sides. One side of this film is printed behind the negative film in such a way that it carries, at regulation distance, only the red-orange pictures. This is accomplished by advancing the negative film two spaces while the positive film is advanced only one. By the same means the previously omitted blue-green pictures are printed in unbroken succession on the other side of the positive film; so that each unit of the film then has the red-sensation picture on one side, and the green-sensation picture on the other, in exact register.

This, however, has some defects. Richer tones and better colour gradations are obtained by the ingenious method adopted for securing that the images on each side are not homogenous, but broken into lines with clear spaces between. This is done in such a manner that the image lines on one side of the film coincide with the clear lines on the other.

The positive film, therefore, is given a " flash " exposure through a species of stencil, or stop-out pattern, on opposite sides. If one side only were exposed under the stencil, and the film developed, it would show a series of longitudinal grey lines, with clear intervening spaces of the same width. If both sides were exposed before development there would be a uniform grey tone. If the lines on

one side were replaced by red-orange dye, and those on the other side by blue-green dye, the two together, on the additive principle, would reconstitute white light. It is obvious that penetration to the other side of the film must be prevented both in printing the stencil pattern and the positive pictures; and this may be accomplished either by adjustment of exposure and development, or by treating the celluloid film with a dye which can be subsequently removed.

It will be seen that the pictures printed on opposite sides of the film are of complementary colour-values, and are printed in the alternate spaces between the lines produced on the positive film by the first exposure through the line screen, and the spaces in which the picture is printed on one side of the film register with the lines on the opposite side for each picture.

This positive film is next developed and fixed in the usual manner, and then both the lines and images on both sides are coloured by any of the usual toning, dyeing, or mordanting methods, to produce complementary colours corresponding to the colour-value of the picture on the opposite side of the film. For instance, the lines and picture on the side containing the red-orange picture are coloured blue-green, and on the opposite side containing the blue-green picture are coloured red-orange.

It will thus be seen that as the lines on one side of the film register with the picture or image sections on the opposite side, the additive colours required for each picture section are supplied by the coloured lines on the opposite side, and as the colours forming the picture cover such lines we get the result of the mixture of the complementary colours on opposite sides of the film. In portions having full density this would be black. In lesser densities, the combination will run all the way from the pure colour of the lines through the various mixtures of the two complementary colours, thus producing the different colours in natural shades in the projected picture. White is produced by exciting the eye with a mixture of the two complementary colours of equal intensities, produced by the oppositely positioned and adjoining red and green lines only.

This process is particularly interesting and important as tending to show that no mechanical difficulties are allowed to stand in the way of working out a colour process. It raises the justifiable hope that although absolute perfection in colour processes has not yet been achieved, there is a practical certainty of further advances, so that we may ultimately be in possession of a perfect process for each and all of the varied applications of colour photography.

CHAPTER XII

Photography applied to Printing

In the application of photographic processes to printing we have the most widely used, and probably one of the most important of all the branches of photographic work. Apart from the field of pictorial illustrations of all kinds, which is now completely held by the various photo-processes, the great bulk of ornamental letterings, designs, and borders, which figure so conspicuously in present-day advertising, would be quite impossible on anything at all resembling this scale without the aid of photography. The requirements of these modern processes have also had a profound effect on the paper and ink, as well as the machinery of the printer; while these again have modified the styles of type used.

The three great services photography has rendered to printing are: (1) methods of rapidly producing printing surfaces capable of printing reproductions of subjects with a literal exactitude that no hand or mechanical method could hope to reach; (2) the preparation of blocks by means of which "continuous" tones can be reproduced in one printing with a black ink of a single hue on white paper; (3) the reproduction in colour of coloured originals in three printings.

In order to understand the principles of these three applications, as well as the actual methods employed, it is necessary to explain briefly the three main classes of printing, namely Relief, Surface, and Intaglio. These classes are named from the nature of the inked surface which presses upon the paper. Fig. 1, which shows a section of each kind of surface, will make the distinction clear.

Relief Printing is much the most important of these classes in the volume of work done, and in the general utility of the processes. The ordinary printers' type is the original and characteristic example of the class. The portions which are to print on the paper

stand higher than the rest, and the ink is applied by rollers to this upstanding surface in an even layer, which is then transferred to the paper by pressure (see figs. 1 *a* and 2). Other printing surfaces in this class are *wood-engravings* or *wood-cuts*, *line* or *zinco blocks*,

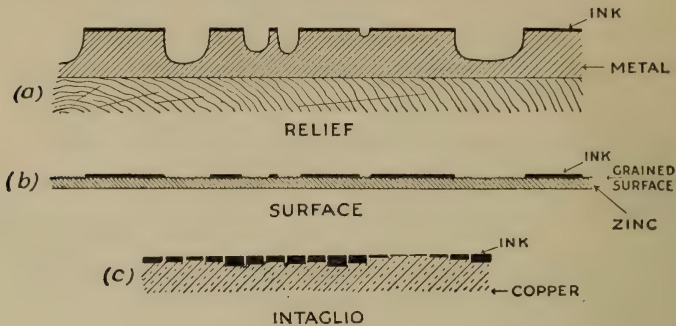


Fig. 1

half-tone blocks, *electros* or *stereos*. The two latter are merely reproductions by electro-deposition and casting respectively of the printing blocks made by the other three processes or from type, while wood-cuts are the original letterpress illustrations, now only used for

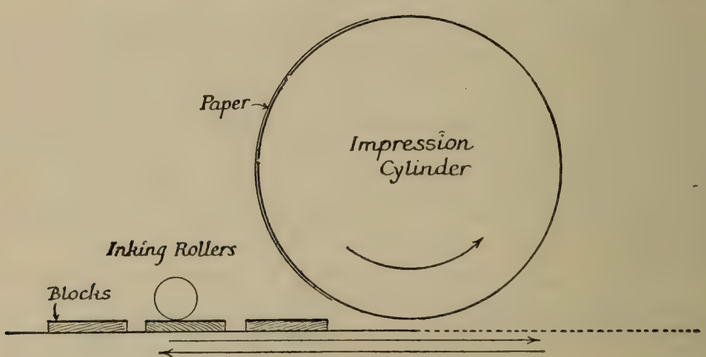


Fig. 2

certain classes of catalogue illustration, having been otherwise completely superseded because of the advantages in cost, speed, and accuracy of the photographic methods employed in line and half-tone block-making.

Surface Printing (see fig. 1 *b*) is worked from plane or cylindrical surfaces with no appreciable relief between the parts which

are inked and the parts which are not. The method of inking is the same as in the relief or letterpress processes, but *the nature of the*

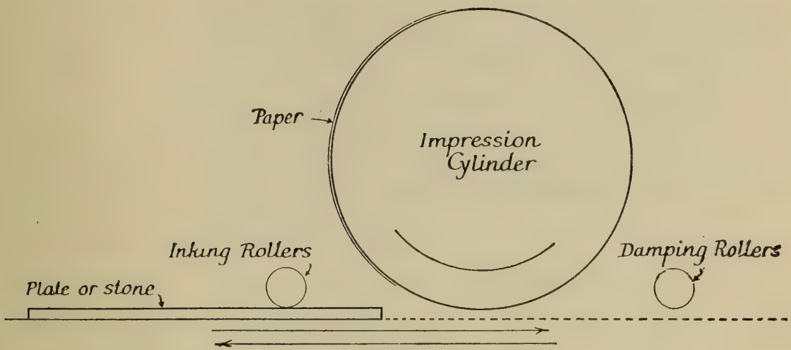


Fig. 3

surface determines which parts take the ink and which do not. The first material used for such printing surfaces was a very fine-grained

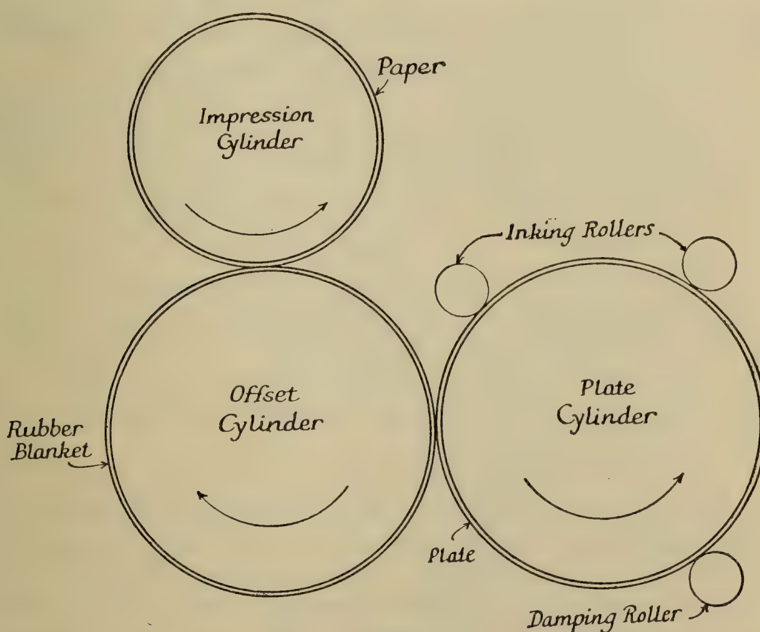


Fig. 4

porous limestone, and the ink-taking parts of the design were drawn or transferred to the surface of the stone in a greasy ink which water

will not " wet ". The stone was kept moist during printing so that the inking rollers only deposited ink on the greasy portions, the moist surface remaining clean. From this use of stone the chief process of surface-printing is called *Lithography*, though the stone has been very largely abandoned in favour of thin zinc or aluminium plates prepared with a mechanically-grained, damp-retaining surface. The ink may be transferred by pressure directly to the paper (fig. 3), as in letterpress printing, or it may be transferred to a smooth, elastic, rubber surface (fig. 4), and from that to the paper, enabling rough-surfaced papers to be printed. The latter method is known as "*offset*"*-printing*, but the printing surface is prepared in the same way as for direct printing.

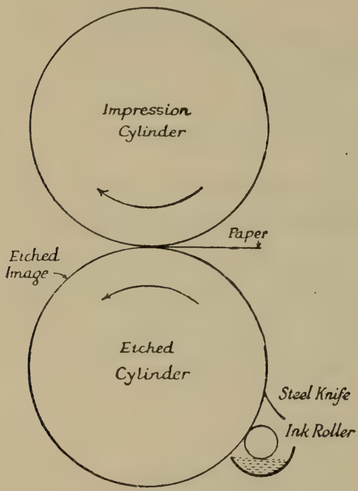


Fig. 5

Collotype, which is a surface-printing process of great beauty and purely photographic origin, has many points of difference from lithography and will require to be described separately.

Intaglio Printing is in a way the reverse of the other two, as the ink is filled into hollows and wiped clean off the surface, so that an intaglio print is a mould in ink of the hollows in the plate (fig. 5), and as these hollows vary considerably in depth the thickness of the ink layer gives intaglio prints a soft, rich quality unapproached by the other classes (fig. 1 *c*). *Steel and copper engravings*, *mezzotints*, and *point etchings* are characteristic intaglio prints, while the photographic processes are known as *photogravure*.

It will be seen that in relief- and surface-printing the principle (i.e. the impressing on the paper of an even layer of ink) is identical, and the difference is in the method; in the intaglio processes the principle (of a varying thickness of ink) is entirely different.

In the application of photography to all three classes there are two distinct steps, the first being the making of a suitable negative and the second the transferring or " printing ", by photographic means, from the negative on to the final printing surface. Attempts to combine the two stages have not yet succeeded in producing a

method of commercial value. The process of making the necessary negative is the same for both relief and lithographic processes, so the following outline serves equally well for either method, the only point requiring notice is that *the processes which print direct from plate*

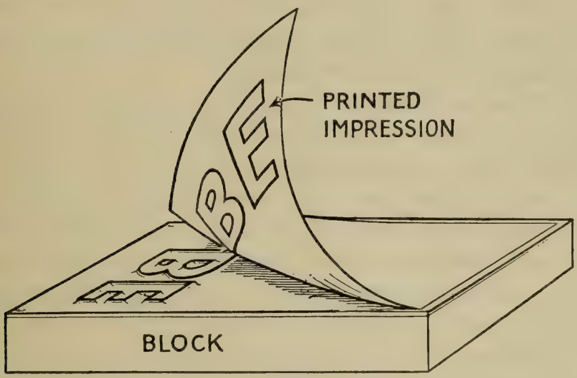


Fig. 6

to paper require a " reversed " negative, i.e. one which is transposed right and left, while if an extra step is introduced, as in offset printing, or in photo-litho transfers, the " direct " negative is used just as in ordinary photographic work. Fig. 6 will make this point clear. The " reversing " may be done either mechanically, by stripping the image-bearing film from the glass and replacing it with the other

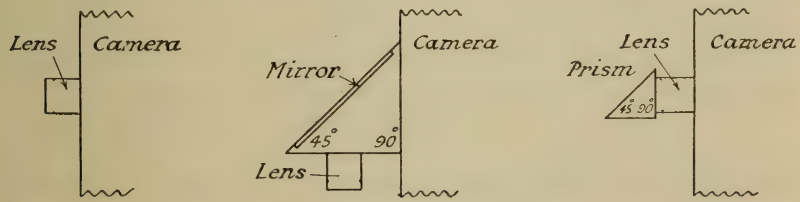


Fig. 7

side down, or optically, by placing a right-angled prism before the lens, or a plane, surface-silvered mirror behind the lens, at 45° to the lens axis (fig. 7).

The Copying Camera.—A strongly built copying camera is necessary, running on rails fixed exactly at right angles to the copy-board, and, in order to avoid vibration, the rails, with camera and copy-board, are slung as one piece from the ceiling or from a stand on the floor. The lens must be thoroughly corrected, particular

attention being paid to definition and flatness of field, but large aperture is not necessary. *The focal length of the lens should be equal to the diagonal of the largest plate used*, anything longer requiring a very long stand to obtain any considerable amount of reduction, while if the focal length is shorter, the space between original and lens, when copying same size or enlarging, is too cramped for the arc lamps used as illuminants.

When we examine the subjects to be reproduced we find they consist of two classes: *line subjects*, which consist of black lines or dots on white paper, and *tone subjects*, in which we have a more or less continuous scale of tones running from black, through the various greys, up to pure white. It will be seen that the first class is much more simple to reproduce, as we have only to produce an ink-taking surface corresponding exactly, line for line and dot for dot, to the original, so we shall consider this class first.

Line Subjects.—In making the negative the various makes of " process " dry plates may be used in conjunction with an energetic but well " restrained " developer such as hydroquinone-caustic potash,[1] which will give sufficient density without intensification, though a slight treatment with Farmer's reducer[1] is advisable in order to remove any slight deposit from the lines and clear spaces, and then the density increased, if necessary, by intensification. In copying line drawings, and indeed for all copying work where crisp definition is essential, it is very important to prevent the light passing through the film from being reflected by the back surface of the plate. This is effected by coating the back of the plate with a preparation which will absorb the light, and plates " backed " in this manner by the manufacturers are readily procurable.

The process which is undoubtedly the best for line subjects, and which is in general use for this work, is the wet-collodion plate developed with ferrous sulphate-acetic acid developer, and strongly intensified so as to give negatives consisting solely of opaque deposit and glass-clear lines and spaces. In addition to the quality of the negatives, the process offers advantages in cost, the ease with which large plates can be prepared as required, and facility in stripping films off the glass for " reversing ", or combining with other negatives.

As the wet-collodion process is obsolete except in connection with this branch of photographic work, a short description of the process as used in the preparation of line or half-tone negatives may

[1] See Appendix, p. 475.

be of interest, while working formulæ will be found in the Appendix. Each plate is coated, sensitized and exposed, developed and finished off while wet, as the name indicates.

Wet-collodion Process.—Collodion is a solution of pyroxyline (cotton which has been treated with a mixture of strong nitric and sulphuric acids, and thoroughly washed and dried) in a mixture of ether and ethyl alcohol. When it is spread over a glass plate the solvents rapidly evaporate, leaving a film which sets to a firm jelly, and if the remaining trace of water and alcohol is dried out it becomes horny and impervious to water. *It is chemically inert in the process, acting merely as a support or vehicle for the sensitive salts.* To the plain collodion is added an iodizer, usually consisting of a mixture of ammonium, cadmium, and strontium iodides and a small proportion of similar bromides and chlorides, dissolved in alcohol with a trace of water. (See Appendix.) The glass plates are cleaned by soaking in nitric acid and thoroughly scrubbing in running water, scrupulous care being taken to avoid fingermarks and to make the surface chemically clean. In order to ensure the proper adhesion of the collodion, the surface of the glass is coated with a very weak solution of hard gelatine, drained, and allowed to dry free from dust. The collodion is poured on the surface of the glass held in the hand, then by careful tilting of the plate is made to flow evenly over the entire surface and drained off. When the coating on the glass has set to a firm jelly, the plate is immersed in a slightly acid solution of silver nitrate, and the transparent film rapidly becomes yellow and opalescent owing to the formation in it of *silver iodide*, the light-sensitive salt on which the photographic action of the plate depends. The plate is merely drained, and the glass side wiped dry, before being placed in the dark slide and exposed.

The sensitiveness is low, and confined almost entirely to the blue, violet, and ultra-violet rays, so that a bright orange-yellow light is used while sensitizing and developing, and the use of enclosed arc lamps, which are very rich in violet and ultra-violet rays, to illuminate the original, enables the exposure to be kept short, even though small stops are used.

The actual formation of the developed image is more of a physical than a chemical action, for though the latent image is formed in the silver iodide within the collodion film, the developer, consisting of ferrous sulphate, acetic acid, and water, reduces only the silver nitrate solution which is still clinging to the surface, and the nascent silver is attracted by and deposited on the film, in pro-

portion to the extent to which the part has been affected by light.

It is thus necessary to conserve the silver nitrate, so development is carried out by holding the plate in one hand, and, with the other, deftly flowing on just so much developer as is necessary to fully cover the plate without spilling. Development is complete in about 45 sec., during which the solution is kept in active movement over the plate by rocking, and finally washed off.

As silver iodide is not rapidly soluble in the ordinary " hypo " solution, the negative is fixed in potassium cyanide solution, and after washing is always intensified, either by bleaching in a solution of lead nitrate and potassium ferricyanide, washing, and blackening with solution of sodium sulphide, or by bleaching in solution of copper sulphate and potassium bromide, rinsing, and blackening with silver nitrate solution, followed, if necessary, by sodium sulphide solution. The fact that the image is entirely on the surface of an inert film enables these very powerful methods of intensification to be used with very brief washing, and the final complete opacity is possible because the grains composing the image are in actual contact, not suspended in a transparent medium as in the gelatine dry-plate.

In producing a printing surface from such negatives, the *bichromated-albumen process* [1] is generally used as a basis for building up the acid-resisting or greasy images required for relief or surface printing plates respectively. A dilute solution of albumen (white of egg), or fish-glue, and ammonium bichromate is flowed over the surface of the metal plate, the excess is thrown off by rapidly spinning or " whirling " the plate, and the plate dried by very gentle heat. Considerable pressure is necessary to ensure perfect contact between negative and metal during the exposure to light, after which the exposed surface is given a thin, even coating of a waxy ink, and immersed in water. The water penetrates the film of ink, dissolving out the albumen coating where it has not been rendered insoluble by light action, and on gently rubbing with a pad of cotton-wool these portions come away, leaving the image in ink lines on a hardened albumen basis with clean zinc between. This image is then brushed over with finely powdered *bitumen* (or " asphaltum ") which adheres to the waxy ink, but can be easily washed off the zinc surface. A moderate heat causes the ink and bitumen to combine into a glossy brown, acid-resisting image.

If the plate is intended for lithographic printing it is now given

[1] For chemistry of this process see Appendix, p. 479.

a short bath in a dilute solution of phosphoric acid in water, which destroys any tendency to scum or greasiness on the exposed zinc surface, while a thin even coating of gum applied to the surface, allowed to dry and then washed off, leaves the plate with image and background with the respective ink-retaining and ink-repelling properties necessary for this method of printing. The lithographic printing press, whether designed for direct or offset printing, carries two sets of rollers, one set to keep the surface of the metal damp, and the other to deposit an even layer of ink on the greasy image (figs. 3 and 4). Aluminium plates are treated in the same way except that different " etching " solution is used.

In map printing, which is done almost entirely by lithography, photographic processes have been very widely and successfully adopted. Specially large and accurate cameras are used, fitted with adjustments for correcting any slight errors in the original drawings which prevent the edges of one sheet exactly corresponding in size with the sheets adjoining.

The ink and albumen method described above is open to the objection, for lithographic work, that the ink image is not in actual contact with the metal, but rests on a film of hardened albumen from which it may strip in printing.

" Vandyke " Process.—A method which is widely used, particularly in connection with map work, is known as the "*Vandyke*" or *reversing process*, which requires a positive picture as the " original " copy in order to produce a positive print, and this process may therefore be used to make a plate for lithographic printing from a printed impression without the use of a camera. The paper on which the " original " is formed must be of even texture, thin, and printed on one side only, and the impression crisp and black. The grained metal plate is coated as in the previous process, but with a solution of bichromated fish-glue[1] in place of albumen, giving a much thicker film. This film is sensitive to light, the glue being made hard and insoluble in water, where it is acted on by light. The original is laid over the prepared plate and exposed to light. A negative image is thus formed on the prepared plate. After exposure, the plate is washed and cleared, thus leaving the plate free from glue where the original is black and coated with a film of glue where the original is clear. The hardened glue is made spongy and soft by treatment with weak acid. The plate is dried and the whole surface coated with a film of " stiff " ink, or a liquid preparation containing ink and

[1] See Appendix, p. 480.

bitumen is flowed on and drained off, leaving a very thin coating. The inky film thoroughly penetrates the grained metal surface of the plate where it is not protected by the glue image, and can only be removed by regrinding the surface of the plate. The places free from glue thus become permanently black as in the original. The inked-glue surface must now be removed; this is done by placing the plate in water and developing it by gently rubbing as in the albumen process described above. The softening and removing of the glue-image and the ink on it is assisted by the use of weak acid or alkali according to the composition of the inky film.

If the production of a relief-printing surface is required, the image is printed on the zinc plate as described on p. 462, but the metal is much thicker and the unprotected portions of the zinc surface are dissolved or " etched " out by dilute nitric acid. The problem here is to prevent any lateral action of the acid which would thin down the lines and destroy the finer work altogether, long before sufficient depth for relief printing had been attained. Several ingenious methods have been devised for this purpose, and though they scarcely come within the scope of the present work, the outline of the chief process is as follows. After a very slight amount of relief has been produced by the action of very dilute nitric acid, the plate is dried, and brushed over with finely powdered dragon's blood [1] in one direction, and in such a way as to pack a deposit of the powder into the corner between one side of the raised lines and the etched surface, while the latter is brushed clean. The plate is heated sufficiently to fuse the dragon's blood powder into a glossy, resistant film, the reason for the employment of this somewhat expensive resin being that it melts into an excellent resistant coating without flowing as ordinary resin does. The other three sides are protected in a similar manner. The plate is again etched, and the powdering and etching repeated till sufficient depth is obtained, when the resistant is cleaned off, the plate further deepened by machining out the wider spaces, and mounted on hard wood to the height of type as used by the printer.

It will be seen that, in this process, the actual relief is not obtained by photographic means, but in the now obsolete " swelled gelatine " and " wash out " processes, a mould is made from which a printing plate is cast or electrotyped. The mould is made thus: a thick layer of bichromated gelatine was exposed under a negative and the unexposed portions of the film allowed to swell in water into relief

[1] A resin obtained from the Malayan rattan palm (Calamus).

in the first process, or dissolved away, leaving the exposed portions in relief in the second process.

The Translation of Tone.—Owing to the method of inking in both relief and surface printing, *a grey, or intermediate tone between the colour of the ink and the paper, can only be rendered by breaking the ink surface up into minute lines or dots and allowing the paper to show between.* In the old craft of wood engraving, this translation of " continuous " tones into black-and-white line or dots was done by the engraver, and the faithfulness of the translation depended en-

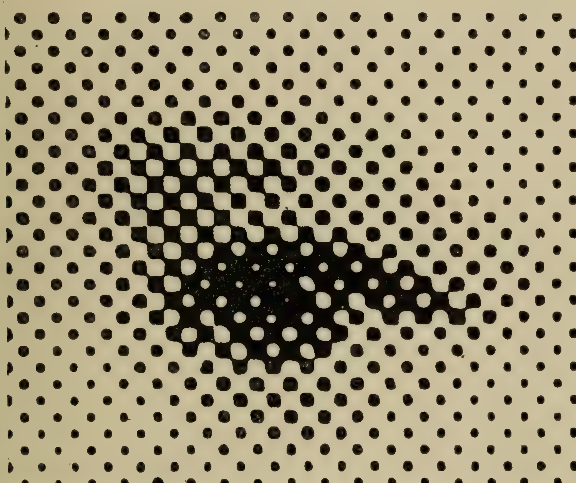


Fig. 8.—The Translation of Continuous Tone into Black and White Units by the Half-tone Process

tirely on his skill; but photography has been successfully applied to this operation in several ways, the two best known being *the Half-tone* and *the Collotype processes.*

The Half-tone Process got its name because it was the first successful attempt to translate the half-tones of a pencil or wash drawing, or a photograph, into a purely black-and-white printing surface. The principle is an optical one, and depends on the introduction of some kind of " screen ", composed of minute opaque and transparent lines or dots, in front of the sensitive plate while copying the picture. The usual form of " screen " consists of two plates of glass each ruled with a series of equal opaque and transparent lines cemented face to face, with the lines crossing at right angles. These cross rulings look like extremely fine wire gauze embedded in the

glass, and the ruling runs from fifty lines per linear inch to 200 or even more, according to the surface of the paper to be used in printing, and the amount of definition required in the reproduction.

A strongly-built type of copying camera is used, provided with a mechanism to bring the " screen " accurately to the correct distance from the sensitive plate after the shutter of the dark slide is drawn out of the way. This distance is an all-important factor in the working of the process, and is adjusted according to the fineness of ruling, camera extension, size of stop, &c., so that the opaque lines cast a soft-edged shadow in the light coming through the lens. To state it differently, each transparent square in the screen throws a spot of light on the plate considerably larger than its own area, brightest in the centre and graduated into darkness at the edges. If a piece of white paper is in front of the lens these tiny graduated spots of light will all register on the plate as dots of equal size, the actual size depending on the amount of exposure given. A short exposure will only record the centre of each spot, while a long exposure will register even the faint outer fringes, and give a much larger size of dot. If we now substitute a wash-drawing or photographic print for the white paper, we find that the varying tones of the picture produce the same effect as the varying exposure to white paper, so that the flood of light through the screen apertures in the high lights of the picture registers as big opaque dots touching at the corners; the middle tones give smaller dots as the faint soft edges have not affected the plate, while in the shadows only the bright centre of the aperture image has been recorded, producing a tiny dot with clear glass all round.

The stencil-like negative is produced by the wet-collodion process, and every negative very strongly intensified. When gelatine dry-plates are used a fine-grain, clean-working plate is developed with a very energetic " hard " developer such as hydroquinone-caustic potash, and intensification is unnecessary.

This process is used in both relief and surface printing, and the half-tone negative can be printed on to the metal by the same process as described for line blocks. The usual coating for relief blocks is a thick solution of fish-glue and ammonium bichromate applied and exposed in the same way as already described (p. 462), but after exposure, the film is at once washed out in water, dyed in a solution of aniline violet to stain the transparent and colourless image, washed to remove excess of dye, dried, and heated very strongly. The heat destroys the dye, and gradually changes the fish-glue image into a

hard, brown, enamel-like coating, which is a very good resistant to either the dilute nitric acid for zinc, or the ferric chloride used to etch the copper more generally employed for half-tone plates.

It is quite possible, with a suitable original, to obtain a " half-tone " print on metal in which the translation of tones is practically perfect, but in commercial work the conditions, and the nature of the originals, result in a considerable amount of retouching or " fine-etching " being required, while even with a perfect print on metal a certain loss takes place during etching, which has to be restored by hand.

In etching half-tone plates no attempt is made to prevent the lateral action of the etching fluid on the dots, so that the dots are being steadily reduced in printing area until the necessary depth has been reached. This fact entails considerable shortening of the scale of gradation from the upper end in the negative, so that the high lights of the original will show a sufficiently large dot on the print to ensure that the necessary minimum depth can be obtained in the spaces between the dots before lateral action makes the dot quite small, and so restores the full length of gradation from white paper to black ink.

The fine-etching is necessary to correct any slight error in the optical translation in the negative, and in the etching of the plate; while it enables considerable sparkle and emphasis to be added to the reproduction, which is necessary for commercial printing. The method adopted is: etch the plate for a time sufficient to ensure that the minimum printing depth is obtained; then the plate is dried, and the lower tones which have reached their correct value are protected from further action by painting them over with acid-resisting varnish and etched a stage further, when another set of tones which have reached the desired value are painted over, and so on until the result desired is obtained. With very good originals only the higher tones require attention, and it is often sufficient to apply etching fluid to them for a few moments with a small brush, as the liquid does not spread if the surface is dry.

The Collotype Process.—Another photographic method of translating continuous tones into black-and-white is used in the collotype process, in which the matted surface of a thick glass plate is coated with a substantial layer of gelatine and potassium bichromate, and dried in an oven at a steady, gentle heat. Exposure to light hardens this film, so that it no longer swells by absorption of water. The exposure is made under an ordinary " continuous " tone

negative, and the plate is then allowed to swell in water. As the gelatine film can only expand laterally towards its upper free surface, it becomes covered with a network of extremely fine wrinkles, or " reticulation ", *which varies in degree according to the depth to which the gelatine has been hardened by light action.* The plate is treated with ammonia and glycerine in water, which increases the reticulation and water-retaining qualities of the film. The film consists of patches of dry, hardened surface and moist, swollen surface, the whole surface being reticulated in varying degrees. Ink adheres to the dry, hardened parts, not to the moist parts, and printing is done from the surface of the gelatine. The grain is " irregular " and usually too fine to be readily detected by the naked eye, but can be made coarse enough to stand transferring to a lithographic stone or plate. The process is a very beautiful and adaptable one, but suited to comparatively small editions, as the life of the gelatine surface averages about 1000 impressions. It is used most extensively in the printing of picture post cards and views.

Photogravure.—The principal photographic *intaglio process* is *photogravure*. The plate was originally inked, wiped, and proved by hand in the same way as a steel engraving or a point etching, but recent modifications have enabled the picture to be etched on a copper cylinder, and the inking, wiping, and printing is done at a high speed by very simple mechanical means (see fig. 5, p. 458).

The photogravure plate has a picture etched into the surface so that the depth of the etching is proportionate to the " depth " of colour in the original. This is done by allowing the etching liquid to act through a negative " carbon " print, in which the thickness of the gelatine varies according to the tones of the original. The etching starts first in the darkest shadows and affects each tone as the liquid progressively penetrates through the thicker portions of the film, until, when the metal is reached through the thickest parts, i.e. the high lights, the etching is stopped and the resistant cleaned off. A plate simply etched in this manner could not be printed from, as in wiping the ink off the surface it would be swept out of the broader shadows and middle tones as well, so that it is necessary to divide up the image by some kind of grain to hold the ink against the wiping action during printing. In the original photogravure, which is printed by hand, this grain is obtained by placing the polished copper plate in a " dusting-box ", which generally takes the form of a tall cupboard with a rotary fan in the lower portion. A small quantity of finely powdered bitumen (asphaltum)

is placed in the box and thoroughly dispersed through the contained air by the action of the fan. The plate is then inserted till a fine, even deposit of bitumen dust settles on the surface, and after this grain is fixed by heating the plate, the carbon resistant is applied and developed with warm water, the copper plate being the " final support ". For the machine-printed gravure this grain is too delicate, and a regular, fine cross-line is applied by re-exposing the carbon tissue under a special screen consisting of fine, clear cross-lines on an opaque ground, and then developing the combined image of cross-lines and picture in position on a polished copper cylinder. The etching liquid is concentrated ferric chloride solution.

The ink used is very inviscid, and consists of the colouring matter in a highly volatile medium. The cylinder is plentifully coated with ink, the excess " squeegeed " off by a thin, flexible steel knife or " doctor ", and the paper pressed firmly in contact with the surface of the cylinder. The cylinders serve for extraordinary numbers of impressions in spite of the continuous wiping contact with the tempered steel edge, and the explanation is that the knife does not clear off all the ink from the surface, but allows a thin film to pass which acts as lubricant, though, owing to thinness of the film and the extremely volatile nature of the ink, it is dry before coming in contact with the paper, which only lifts the moist ink out of the etched hollows. Compared with an impression by the half-tone process used for relief and surface printing, and which consists of dots of varying size, but equal density of ink, a machine-gravure impression appears formed of dots of approximately equal size, but varying widely in density of ink, the etching being like an extremely minute and shallow honeycomb with cells of varying depth.

Unlike the half-tone relief plate, no " fine etching " can be done on the copper cylinder, although the gradation as a whole can be considerably modified by the use of ferric chloride solutions of different concentrations, each having a different density, and, therefore, a different rate of penetrating the gelatine resistant. All the errors due to faulty photography in making the negative and the diapositive must be rectified, as well as any improvements on the original carried out by working up on the negative or positive, before making the resistant.

The Three-colour Process.—The third important application of photography to printing is the reproduction in colour of coloured originals. No purely photographic process has as yet equalled the

printing-press in producing uniform colour-pictures in large numbers. The process was shown to be a practicable one by Clerk-Maxwell, and it depends upon the way in which the eye perceives colour.

If we analyse a beam of daylight by passing it through a prism of glass, we get a continuous spectrum, showing that the light consists of an unbroken series of waves of different refrangibility and wave-length, each wave-length giving the sensation of a different colour. If we pass this spectrum through a long-focus lens, we can recombine all the colours into a white image again; but if we place in front of the large lens an opaque screen, and pierce holes in the screen so that only a portion of the red, the green, and the violet parts are allowed to pass and recombine, we find that by a little adjustment of the sizes of the apertures we can again get a white image which our eyes cannot distinguish from that formed by the continuous spectrum. If we close the aperture in the violet, the image becomes a pure yellow though no yellow light is present, and so on.

On these and other similar experiments the Young-Helmholtz theory of colour-vision is based, and the three-colour process of reproduction is a practical application of this theory.

The hypothesis is that colour-sensations depend on the action of three independent physiological processes, each stimulated by a particular range of wave-lengths, though there is a certain amount of overlapping. If these three " sensations " are equally stimulated we perceive white, and so long as the stimulation is equal and sufficiently intense, our eyes cannot distinguish whether it is caused by a continuous spectrum or by three isolated wave-lengths each stimulating one sensation.

When each sensation is stimulated separately, the colours we perceive are *red* (scarlet), *green* (emerald), and *violet* (bluish); while if two sensations are stimulated, we get colours which approximate to those which the artist considers his primary colours, but which we must call complementary, or *minus* colours, for, if added to light which stimulates the remaining sensation, we get the complete sensation of white, or, to state it in the most useful way for our present purpose, the colour produced by stimulation of two sensations is white *minus* the colour-sensation not stimulated. In our experiment we found that when we closed the aperture in the violet, the remaining red and green stimulation gave yellow, so we call yellow " minus violet " because we got the sensation of yellow by subtracting violet from white.

The following table will make the relation of these colours more clear:

Colour-sensation Stimulated.	Colour Perceived.	Minus Colour Perceived.	Colour-sensation Stimulated.
R, G, V	White	Black	None
R only	Red (scarlet)	Blue (greenish)	G, V
G only	Green (emerald)	Pink (magenta)	R, V
V only	Violet	Yellow	R, G
R, G	Yellow	Violet	V
R, V	Pink	Green	G
G, V	Blue	Red	R
$\frac{1}{2}$R, $\frac{1}{2}$G, $\frac{1}{2}$V	Grey	Grey	$\frac{1}{2}$R, $\frac{1}{2}$G, $\frac{1}{2}$V
$\frac{1}{2}$R, $\frac{1}{2}$G.	Brown	Violet (pale)	V, $\frac{1}{2}$R, $\frac{1}{2}$G

and so on.

By varying the degree of stimulation of the three sensations, the effect of any colour can be produced, but it must be kept in mind that the above table deals with the addition of coloured lights, and not with mixtures of pigments or dyes.

Clerk-Maxwell pointed out that by using three transparent coloured media, or " filters ", each transmitting only the wave-lengths which stimulate a single sensation, and given a plate sensitive to the whole spectrum, it would be possible to record, as three monochrome photographs, the varying stimulation of each sensation by any coloured object or view, and that these records could be used in two ways to reconstitute a coloured image which the eye would be unable to distinguish from the colours of the original.

The two methods of using these sensation records are known as " additive " or " subtractive ", according to whether the colour-image is obtained by *adding* together the three records as lights, or by using them to successively *subtract* the reflecting power of a white surface for their respective colour-sensations. *Only the second, or subtractive method, can be used in printing.*

The principle of this method is readily grasped if we approach it by way of a simple black-and-white drawing, of which the stencil-like negative is obviously a record in opaque deposit of the amount of *white* light reflected by the drawing; the black lines, which reflect practically no light, remain transparent.

In order to reproduce our drawing on white paper by the printing-press, we must destroy or *subtract* all the reflecting power of the white paper in those parts which correspond to the black lines of the drawing. This is done by preparing a printing-plate in which

the transparent, non-recorded, or *minus* parts of the record are the ink-taking portions, and we use an ink which subtracts *all* the light-reflecting power, so its colour is therefore " minus white ", i.e. black.

Applying this to our three colour-record negatives, we see that in the one made through the violet filter all parts which did not reflect violet will be transparent, and consequently will be the parts which will deposit ink on the paper. The ink used must subtract the reflecting power for violet, but not for green or red, that is, its colour will be white minus violet, which we have seen is yellow. Similarly, the printing of the red record requires a minus red ink, i.e. greenish-blue, and the green record requires a minus green, i.e. magenta-pink.

The block made from the negative taken through the blue filter is the first block printed. It is printed in yellow ink on a white glossy paper. Then the block made through the green filter is printed in magenta ink on the top of the yellow print, and finally the block made through the red filter is printed in greenish-blue ink. All three printings must be in exact " register ", i.e. any set of lines on each block must be exactly superimposed.

The great bulk of commercial colour work is done on the panchromatic gelatine dry-plates, but on the Continent collodion emulsions sensitized to the portion of the spectrum required are widely employed.

In practice there are five essential operations involved: (1) the analysis of the image of the coloured original in terms of the three mixing colours, (2) the translation of the three records into black-and-white units as explained under the half-tone process, (3) the preparation of the three printing-plates, (4) the skilful correction of the colour-values on these plates so as to reproduce the original when (5) the three plates are printed in their respective colours so that the impressions are accurately superimposed.

The analysis (1) is made by passing the light, either before or after it passes the lens, through a coloured medium or " filter " which absorbs all the rays except those required. Each filter passes approximately one-third of the spectrum, with a small amount of overlapping, and the visual colours of the filters are red, green, and violet, thus corresponding roughly to the primary sensation-colours of the Young-Helmholtz theory of colour-vision, but as the filters have to be adjusted to the relative colour-sensitiveness of the photographic plates used, they may depart widely from these colours as far as visual appearance goes.

The filters may consist of coloured liquids contained in a glass

cell with optically worked flat sides, or else of stained films of gelatine or collodion cemented between thick, optically worked glass plates. The latter is the form generally used since the use of commercially sensitized gelatine dry-plates became the rule, and the makers of the plates supply standardized filters adjusted to the spectrum colour-sensitiveness of their plates.

When the range of contrast in the original is not too great, and lighting, depth of field, and other difficulties do not present objections, the operations (1) and (2) may be combined by working with the cross-line screen in front of the plate, but otherwise three continuous-tone colour-record negatives are made first, from which positives on glass are made, and from these in turn the three half-tone screen negatives are produced. In either case care has to be taken that the screen is rotated 30° between each negative, otherwise a very objectionable pattern or "plaid" effect is produced.

The preparation of the printing-plates (3) is exactly similar to the ordinary half-tone process previously described, for either letterpress or lithographic printing, but the correction (4) or fine-etching is different in principle, though similar in method, to the work done in black-and-white in order to produce a more brilliant result than the purely mechanical process yields. In either case the continued action of the etching fluid not only increases the depth between the dots of the image, but gradually reduces the printing area of the dots themselves, so that the whole picture becomes lighter in tone. The etcher takes advantage of this by painting out parts of the picture which are of the desired strength and allowing the rest to go on etching. In black-and-white work this calls for some skill and judgment, though the work can be watched practically all the time as it will print finally, but in colour work the etcher has to go over the colours of the original, and, thinking of them in terms of various-sized dots of the three-colour inks to be used, etches each plate to correspond. The amount of work necessary in this way is always considerable, and the chief reason is to be found in the inks used in the printing operation (5).

One of the obstacles to the preparation of lithographic plates of the same approximation in colour-rendering as can be done by letterpress blocks is that, as there is no etching, there is not the same opportunity to effect this necessary correction.

The theoretical requirements of the inks are that they should be (1) transparent, (2) permanent, (3) should absorb all the rays transmitted by the corresponding filter and recorded by the plate.

It has so far proved impossible to obtain all these qualities at one time, and the necessary compromise involves the greater part of the handwork which is required to give a correct reproduction of the original, though defects in the colour-sensitiveness of the plates, in the colour filters, and the general manipulations tend to produce a cumulative error in the correct colour reproduction. The visual colours of the inks which fulfil the theoretical requirements are *yellow* for the plate prepared with the violet filter, *magenta-pink* for that from the green filter, and a *greenish-blue* for that from the red filter. In practice the yellow can be obtained with a fair approximation to the required properties, but instead of magenta-pink a rather heavy red inclined to scarlet has to be used, while the blue has little suggestion of a greenish shade and often is rather purplish.

It is usual to work with filters adjusted for the theoretical inks, and work up the result by hand-etching on the plates to suit the particular three inks to be used in printing. The variety of shades of ink used in three-colour work is very wide, and no serious attempt has been made to standardize them, partly because the same compromise with theory does not suit a sombre subject as well as it might a light, brilliantly coloured one, and the nearer the inks approach the purity and intensity of the theoretic colours, the more exacting are the demands on the printer.

The production of a pure grey or black by the superposition of three brilliant, transparent colours is a difficult task, as the delicate balance of the three colours necessary is not easy to maintain in commercial printing, so a fourth printing is sometimes added in grey-black, which steadies the greys, and adds richness to all the darker tones. This plate is usually prepared from a negative made through a fully-correcting orthochromatic filter; but this serves merely for the basis of the finished plate, which is a product of art rather than science.

A very considerable number of bright colours, such as emerald-green, purple, and violet, cannot be reproduced in their correct purity by any mixture of the inks, while, since the half-tone process impression consists of dots surrounded by white paper, the effect of contrast is to make what should be a pale-blue sky, for example, appear grey, and tints consisting of fine red dots suffer a similar degradation. Only the tints of yellow escape this effect, since the colour is so luminous that the contrast effect does not occur.

In colour reproductions by offset lithography, where the low

cost of the plates and the high printing speed render it possible to increase the number of printings without unduly increasing the cost, this difficulty with regard to light tints has been largely overcome by adding extra printings in pale red and pale blue, thus virtually splitting the red and blue into two parts, while the lack of crispness which the increased number of superimpositions is liable to introduce is covered by crisp, worked-up printing in black.

On theoretical grounds photogravure would appear to hold most promise of further development in the reproduction of clean, bright colours, as the degrading effect of contrast between dots of intense colour and white paper would not be present, for light tints would be rendered by a practically continuous, extremely thin deposit of ink, while rich, dark tones would be ensured by the considerably thicker layer of ink in these parts.

The difficulties which have stood in the way of commercial three-colour photogravure have been registration of the images, and the delicate retouching necessary, but these difficulties are being overcome, and the near future should see the process being worked commercially.

Appendix

The following notes are compiled with a view to enable the reader to make use of the various processes, either as described or in some other application.

1. *Developer for Line and Half-tone Negatives on Dry Plates.*

(A) Hydroquinone,	25 gm.	(B) Potassium hydrate (stick),	50 gm.
Potassium metabisulphite,	25 gm.	Water,	1000 c.c.
Potassium bromide,	25 gm.		
Water,	1000 c.c.		

These stock solutions keep well, but the working solution must be mixed immediately before use, and used for one plate only.

For use, take equal parts A and B, and develop for $2\frac{1}{2}$ to 3 minutes at 65° F. The temperature is a very important factor with this developer, and must be kept between 60° and 70° F. for satisfactory results.

Fix in " hypo " solution containing 2 per cent potassium metabisulphite, and wash well.

2. *Hypo Solution.*

Hypo (sodium thiosulphate),	250 gm.
Water,..	1000 c. c.
Potassium metabisulphite, ..	20 gm. (added to the cold solution).

3. *Reducer for Dry Plates.*

(A) Hypo, ...	200 gm.	(B) Potassium ferricyanide,	10 gm.
Water, ...	1000 c. c.	Water,..	100 c. c

If there is a slight veil, it is removed by soaking the fixed and washed negative in fresh plain hypo solution, pouring off the solution, and adding to it enough potassium ferricyanide solution to colour it a strong straw colour, pouring evenly over the negative and rubbing gently with a swab of cotton-wool till the veil is just removed, then immediately washing thoroughly.

Intensification should not be necessary if the original is pure black-and-white, but if faint or yellowish, intensification is resorted to by either of the following methods:

4. *Mercury and Ammonia Intensifier.*

(A) Mercuric chloride,	60 gm.	(B) Ammonia (0·880),	200 c. c.
Hydrochloric acid,	5 c. c.	Water, ...	1000 c. c.
Water, ...	1000 c. c.		

The negative is bleached in A, and, after thorough washing, is blackened in B, washed, and dried.

5. *Lead Intensifier.*

(A) Lead nitrate, ...	46 gm.	(B) Sodium sulphide,	50 gm.
Potassium ferricyanide,	70 gm.	Water, ...	1000 c. c.
Acetic acid, ...	20 c. c.		
Water, ...	1000 c. c.		

The negative is bleached in A, washed till white, rinsed in 2 per cent nitric acid, washed, and blackened in B, then washed and dried.

This method is interesting as affording a means of transforming the image into one of another metal. If the negative, after being bleached, is soaked in weak hypo solution, the silver, in the form of ferrocyanide, is dissolved, and an image of lead ferrocyanide remains. Several other metals may be used instead of lead.

Wet Collodion Formulæ

6. *Gelatine substratum.*

Sheet gelatine, ...	2·5 gm.
Distilled water, ...	1000 c. c.
Ammonia (0·880), ..	5 c. c.

Cover the gelatine with a portion of the water in a small beaker and allow to swell, then place the jar in a vessel of boiling water and stir till

dissolved. Add this solution to the rest of the water, then add the ammonia, and filter carefully through white filter-paper.

7. *Collodion.* (It is not advisable to make up the collodion and iodizer, as a number of standard makes are more reliable.)

(A) *Collodion.*		(B) *Iodizer.*	
Pyroxyline, ..	24 gm.	Cadmium iodide, ..	7·4 gm.
Ether (0·720), ..	660 c. c.	Ammonium iodide,	4·6 gm.
Alcohol (0·802), ..	440 c. c.	Strontium chloride,	1·4 gm.
Iodizer solution (B),	100 c. c.	Calcium chloride, ..	1·4 gm.
		Alcohol (0·802), ..	1000 c. c.

The iodized collodion should be a deep straw colour. If too pale, add a drop or two of tincture of iodine (iodine 0·5 gm. in 100 c. c. alcohol), while if too red, a piece of cadmium foil should be added. If the collodion becomes too viscous, it may be thinned with a mixture of 2 parts ether to 1 of alcohol.

8. *Sensitizing Bath.*

Silver nitrate, ...	80 gm.
Water (distilled), ..	1000 c. c.
Nitric acid, ...	8 drops.

This solution should be just sufficiently acid to slowly change blue litmus-paper a *faint* pink. When the first collodionized plate is placed in the solution, it will be found to be thin and almost transparent, as the silver nitrate solution takes up a certain small amount of silver iodide as it is formed, and it is advisable to leave the *first* plate in overnight.

The glass plate is held by the corner in the left hand, as level as possible, and a pool of collodion about quarter the size of the plate poured on with the right hand. A gentle tilt makes the collodion flow evenly successively to the top right-hand, top left-hand, bottom left-hand, and bottom right-hand corner, where it is drained off by *slowly* bringing the plate to the vertical, rocking it meantime with the draining corner stationary. With practice it is possible to obtain a perfectly uniform coating even in very large sizes. When the coating is firm enough to take an impression of the finger at the draining corner, the tray containing the silver solution is raised at one end by the right hand, the plate is carefully laid on the exposed part of the bottom, and the dish lowered smartly so that the solution flows in an even wave over the surface. After rocking for about three minutes, the plate is raised by means of a hook of pure silver wire, and if the film has lost all appearance of greasiness, the plate is lifted up, drained, and the glass side wiped dry with blotting-paper, when it is ready for exposure, which must be completed and the plate developed before the silver solution begins to dry on the film.

The coating may be done in white light, but immediately the silver

solution flows over the plate only orange light is used till development is complete and the plate washed.

9. *Wet-plate Developer.*

Ferrous sulphate, ..	50 gm.
Acetic acid (glacial), ..	50 c. c.
Water, ...	1000 c. c.

This solution keeps fairly well, and is used as described in the text. The addition of 30 c. c. alcohol assists even flowing when the silver solution becomes alcoholic through prolonged use.

10. *Fixing Solution.*

Potassium cyanide (95 per cent),	50 gm.
Water, ...	1000 c. c.

Fixing and intensifying solutions may be poured on the negative held in the hand as when developing, but the solution flowed over repeatedly till action is complete. If constantly used, it is more economical to use trays.

11. *Copper and Silver Intensifier.*

(A) Copper sulphate,	100 gm.	(B) Silver nitrate, ..	50 gm.
Water, ...	500 c. c.	Water, ...	1000 c. c.
Potassium bromide,	100 gm.	Nitric acid, ..	5 c. c.
Water, ...	500 c. c.		

The copper sulphate and potassium bromide are dissolved separately and mixed to form solution A.

After the fixed and washed negative is bleached in A, it must only be evenly *rinsed* well, back and front, before blackening in B, as the white image is partly soluble and may not blacken if washed too long.

If still more density is required, a solution of sodium sulphide (Formula 5B) is flowed over till the whole image becomes dense black sulphide. Lead intensifier (p. 476) is also highly suitable.

12. *Iodine Solution.*

Iodine, ...	10 gm.
Potassium iodide, ..	20 gm.
Water, ...	1000 c. c.

Mix the iodine and iodide, add barely enough water to cover, shake, and when dissolved add the rest of the water.

This solution is used in two ways in order to clear up the transparent parts of the negative. If enough is added to a quantity of water to make it a sherry colour, and a few drops of cyanide solution (Formula 10) are then added till the colour is discharged, the solution is a very good reducer, which may be used either after fixing or after intensification with copper-silver, but it is only effective for a few minutes after being mixed.

In the other method the iodine solution is used alone as a bleacher after copper-silver, converting the image into silver iodide, which a very weak solution of potassium cyanide will slowly dissolve, attacking first the isolated grains, which are causing the veil, and removing them without perceptibly affecting the density of the compact grains of the opaque parts. The negative is then blackened by treatment with sodium sulphide solution (Formula 5B), which converts the image into silver sulphide.

Collodion negatives are very readily scratched, and should be varnished with an ordinary spirit negative varnish, but if a single print is required it may be sufficient protection to flow over the wet negative a 10-per-cent solution of gum arabic in water.

Where images of extremely fine grain are necessary, another collodion process is utilized in which the collodion contains bromides in place of iodides, and a neutral silver nitrate solution of nearly twice the concentration is used. The sensitized plates are thoroughly washed to remove the silver nitrate, bathed in a solution of tannin, and dried in the dark. These plates can be exposed in the camera or in contact with a negative, but the sensitiveness is very low. After exposure the plate is soaked in water and developed in an alkaline hydroquinone developer, fixed in hypo, and intensified with any of the foregoing intensifiers. Space does not permit of details of this useful process being given here, and reference should be made to *The Wet Collodion Process*, by Arthur Payne, for further particulars of both processes.

Bichromated-albumen Process.—In this and all other processes employing gelatine, albumen, gum, or similar substances, it is all-important that the surface to be coated should be perfectly freed from grease, and it may save much disappointment to note that the surface of metals which have been polished by "buffing" cannot be perfectly cleaned by chemical means other than dissolving away the surface, and, as this is apt to proceed unevenly, it is best to remove the surface layer mechanically by rubbing with finely powdered pumice or emery.

13. *Albumen Sensitizing Solution.*

White of one egg (medium size).	
Ammonium bichromate, ..	6 gm.
Water, ...	300 c. c.

Separate the white carefully from the yolk, add to half the water, beat up well, allow to settle, and use the clear liquid. Dissolve the bichromate in the remainder of the water, mix together, add ammonia (0·880) drop by drop till the orange colour becomes a full yellow, and filter carefully. If too much ammonia is added, the whole of the bichromate will be converted into chromate, as shown by the colour becoming a lemon yellow, and the sensitiveness will be much less. With no ammonia, it is almost impossible to keep the coating from becoming insoluble

spontaneously in the extremely thin layers necessary in this process.

The ink used is supplied under the name of "Photo-transfer Ink".

14. *Fish-glue Sensitizing Solution.*

Fish-glue, ...	100 c. c.
Ammonium bichromate,	6 gm.
Water, ...	200 c. c.

As in the case of the bichromated-albumen solution, the addition of a few drops of ammonia is necessary to ensure clean working.

The solution will keep for a week, but the coated plates must be exposed and developed immediately, or the coating will become insoluble all over.

15. *Dye Solution.*

Methyl violet dye,	25 gm.
Water, ...	1000 c. c.

Etching Solutions.—Nitric acid is only used for etching zinc, as the fumes of nitric oxide, given off in the case of copper, brass, and other metals, are very objectionable and poisonous.

As the object in etching zinc is generally to keep the image from being thinned down, a very dilute solution (not more than 2 parts of acid in 100 of water) is used in the early stages until the sides of the lines are protected. The strength is increased with each bath up to 25 parts of acid to 100 of water, but is adjusted to the fineness of the subject.

Copper, brass, bronze, nickel, iron, and various alloys are etched with ferric chloride solution, the strength of which is usually read with a Beaume hydrometer. A saturated solution of commercial "perchloride" gives a reading of fully 45 Beaume, and etches very slowly and smoothly. The usual strength for etching is 40, and further dilution gives increased rapidity in etching with a corresponding rougher edge to lines till about 25, when the action begins to get slower again.

CHAPTER XIII

The Technics of Kinematography

The kinematographic industry depends for its existence upon the application of scientific laws and principles. Chemistry, optics, and mechanics govern all its branches, both in the production of its material and in the presentation of its effects.

The invention of celluloid made kinematography possible. Its introduction was soon followed by the presentation of moving pictures, crude certainly, but sufficiently interesting to cause quite a rage. Interest in pictures has continued, and now the products of the kinematograph are almost as important as those of the printing-press. Many inventors are busy trying to produce satisfactory moving pictures in natural colour at a cost commercially practical. This problem is still unsolved.

The chemical side of the industry lies in the production, development, and preservation of the film. The optical side deals with lenses, finders, the projecting machine, and the suppression of flicker. The mechanical problems, however, in their variety and number, far exceed those of the other sciences, and the mechanic has had to overcome the greatest number of difficulties in connection with the subject. In the commercial production of moving pictures change and improvement are of almost daily occurrence, and finality of method seems as far distant as ever.

There are four principal appliances necessary for the production of the screen picture: the camera, the perforator, the printer, and the projector. These must all work in complete accord, and shortcoming in any one will leave its mark on the finished picture when shown on the screen.

Moving pictures depend on the fact that when we look at an object, its impression on the retina remains for a fraction of a second after we cease to receive its impression. The time the impression persists depends upon the brightness of the object viewed; its dura-

tion has been variously estimated by different investigators, the average idea being that one-sixteenth of a second is the time of persistence of an ordinarily illuminated object. This period of time has become the standard rate of exposure in the kinematograph camera and in the projector. Pictures each 1 in. wide by $\frac{3}{4}$ in. high are thrown on the screen. Each picture remains still for about one-twentieth of a second, a shutter cuts off the light, and the next of the series is substituted. Each succeeding picture differs slightly from the preceding one. During the passing of the shutter the screen is black, but the image of the picture remains on the retina, and before it sensibly fades the next picture takes its place.

The highly illuminated parts of the screen tend to persist longer in the eye than those less bright, and two images of a moving object may often be seen. This constitutes a defect which it is practically impossible to eliminate. It is hardly noticeable when the photographic quality of the film is good. Hard, under-exposed prints exaggerate the defect. In using the camera the same speed is maintained, except in cases where it is desirable to make the movement on the screen appear either more or less rapid than the original. "Slow-motion" pictures, useful in cases where it is desired to see what happens to quick-moving objects, are produced by photographing the subject at a much greater rate than that at which it is to appear on the screen. The opposite treatment produces the opposite effect.

The practical procedure in the production of moving pictures is as follows.

The film from the factory is perforated to permit of its being fed through the camera during exposure. The negative is developed, and by means of the printing machine a positive is produced on a correspondingly perforated film. After being joined up the positive is ready to be thrown on to the screen by the projector.

The width of the film is $1\frac{3}{8}$ in. This was the original size of Edison's kinetoscope films, and it has now become the standard width. Till comparatively recently much confusion was caused by slight variations in the width of film, and in the gauge and sizes of the perforation. This difficulty has been practically overcome by collaboration between an English and an American committee, who have devised standard measurements for all interchangeable materials and parts of machines (fig. 1).

The Film.—Celluloid is a flexible transparent substance almost unaffected by water. There are two distinct varieties—aceto-

cellulose and nitro-cellulose. The latter is used for the greater number of films, and it is very inflammable, being chemically almost identical with gun-cotton. Aceto-cellulose is not inflammable, but unfortunately it is not so suitable as nitro-cellulose for use in conjunction with photographic emulsions.

Nitro-cellulose film is pliable and transparent when first made; it is also tough and strong. It will retain these qualities for a long time if suitably treated. For use in kinematography it is supplied in

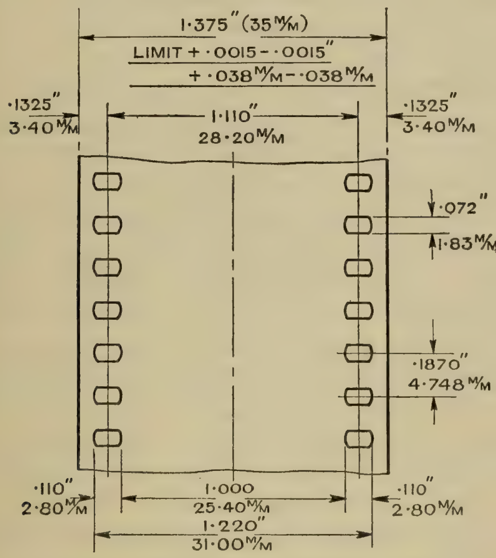


Fig. 1.—Standard Sizes of Undeveloped Negative

lengths of 400 ft., $1\frac{3}{8}$ in. wide, coated with gelatine emulsion. It is dangerous to use in any situation where it is liable to become ignited.

All public exhibitions of the kinematograph are under special legislation. The regulations enforced when films are publicly shown render the exhibition of kinematograph pictures as safe as any other form of entertainment.

Nitro-cellulose gradually shrinks in size, becomes less transparent and less pliable with age. The time taken in these changes varies with the treatment to which it is subjected, but if carefully packed and hermetically sealed it is doubtful if films could be used after fifty years storage. In general use, owing to the heat of the projector and the damage by continuous handling, four to six months of usefulness is the most that can be hoped for.

Nitro-cellulose, like amber, develops static electricity when subjected to friction. In some climatic conditions the act of unrolling the film generates sparks sufficiently powerful to act on the photographic coating. Many pictures have been lost through this defect.

Celluloid film is made by dissolving celluloid in certain volatile fluids. A thick viscous solution results, having the property of setting into an even coat when a layer is poured on to a level surface, such as glass very carefully joined. The solution is allowed to dry, forming a slightly adherent film, which can be stripped off. Lengths of film are then cemented together and coated with photographic emulsion, cut into widths of $1\frac{3}{8}$ in., and after being rolled tightly, packed carefully to prevent air or moisture reaching them.

The next process is that of cutting the perforations. This must be carried out with extreme accuracy, the final result on the screen being greatly influenced by the condition of the perforation. Unless this process be perfect the finished picture cannot be perfect, but it does not follow that perfect perforation will produce steady pictures. Film is now often sent out from the factory already perforated and packed in such a way that it may be reasonably expected to retain its photographic qualities for two years if not opened. It must not be subjected to heat above 70° F., but cold, down to 10° below zero, does not seem to adversely affect it.

When taken into extreme climates, great care is necessary to prevent deterioration of film. A very hot humid condition is perhaps the most liable to cause trouble. Bacterial growths may attack the gelatine coating, and it is advisable to develop negatives as soon as possible after exposure. Hot dry atmosphere and extreme cold both tend to the production of electrical or " static " markings. Special care in handling the film under such conditions is therefore necessary. Many mechanical appliances are used in the manufacture of film. They are of little interest to any but those actively engaged in its production—except the perforator. Until recently every maker of pictures obtained the film in an unperforated state, preferring to perforate to his own measurements to suit his own machines, but since the dimensions have been standardized, film is often sent out already perforated.

The Perforator.—Many different forms of perforating machines have been used. Recently, owing to standardization of sizes, the perforator is approaching a standard type.

The machine is a critical one in many ways; on it the first step towards steady pictures depends. It has to deal with an unstable

substance and yet produce definite results. Celluloid apparently repels water, nevertheless if a piece of celluloid of known length be immersed in water for twelve hours, it will increase in length to a small extent. If it then be thoroughly dried, it will be shorter than its original length. Photographically coated film shrinks considerably during its development and subsequent drying. This is greatly due to the gelatine, which contracts during the process, and it has to be allowed for in perforating. The negative film is perforated to a gauge calculated to allow the treated film to approximate as closely as may be to the gauge of the unexposed positive film, which

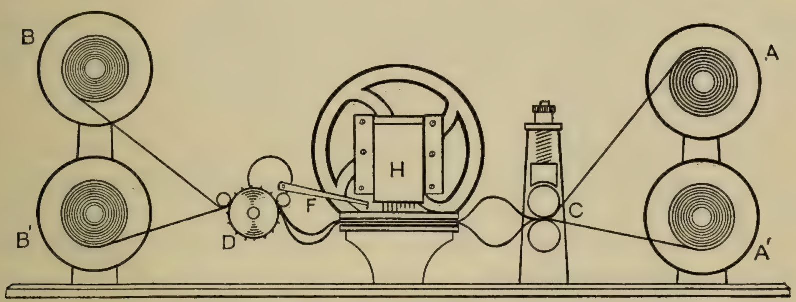


Fig. 2.—Diagrammatic Representation of Component Parts of a Perforator arranged to perforate two films at one operation

A, A′, Rolls of film to be perforated. B, B′, Perforated film being wound up. C, Feed rollers. D, Take-up sprocket. F, Feed claw (intermittent movement). H, Punch slide, carrying punches and dowel-pins.

is also longer than the desired gauge of the perforation in the finished picture.

The perforating machine (fig. 2) works as follows.

A series of punches, sometimes two, sometimes eight, is fixed to a sliding carrier which works in guides vertically above the film. The punches are evenly spaced, and at even spaces beyond them are fixed some pins of the same section as the punches. These are called " dowel " or " pilot " pins, and their function is to enter and fit the previously perforated holes, and so set the film in the exact position required before the next set of holes is pierced. The punch-carrier is moved up and down by a crank or cam carried on a spindle, which is geared to a claw or other mechanical device by which the film is advanced the required distance between the successive descents of the punch-carrier. The roll of unperforated film, heavy at the start of the operation, would cause a drag on the claw movement. To obviate this the film is unrolled evenly by a pair

of rollers which deliver it to the claws and punches at the necessary rate. After the film is perforated, it passes over a sprocket-wheel and on to a rotating spindle by which it is wound into a roll. A slipping device or " tension " allows the roll to rotate more and more slowly as the roll increases in diameter, the sprocket-wheel preventing the film from pulling against the sides of the dowel-pins. Any tension acting against the sides of the pins or punches would cause unevenness in the perforations, so a loose loop of film is arranged both before and after the film arrives at the claw and punch mechanisms.

Till recently perforators were made adjustable as to gauge, but now machines are often devoid of this refinement. In passing through the machines, only that part of the film intended to be perforated is guided, leaving the picture space (1 in. wide) untouched by the machine.

Perforation (the most critical mechanical operation necessary in the production of pictures) is now often undertaken by the film makers. This is as it should be, because the less the film is exposed to the air and the light of the dark room and the less it is handled before exposure the better.

The Camera and its Fittings.—The perforated film is now ready to receive its exposure in the camera. The mechanism of the camera must be very carefully fitted, and its parts so balanced that the necessary rotation to cause 16 pictures per second to be taken will not impart vibration to the whole apparatus. The tripod or other stand upon which the camera is fixed must be sufficiently strong and rigid to resist the pressure due to turning the driving-handle of the machine. Means are also provided by which the camera when on the stand can be turned in any direction. Moving objects can thus be followed and kept within the limits of the picture. The horizontal and vertical movements are produced by turning handles at the top of the stand just below the camera. This part of the stand also requires careful construction to avoid shake in the parts and a consequent jerky movement in the picture. The gears which operate these parts can be quickly thrown out of action, and the camera pointed immediately in any direction and again fixed by throwing the parts into gear.

The legs of the stand are extensible in order that the height of the camera from the ground may be varied. It is often necessary to be able to photograph over the heads of people who may be viewing a procession or a football game. Sometimes the camera is required

to be near the ground, and special stands are often necessary for special purposes.

To produce good results when taking panoramic pictures or when following a moving object, the mechanism of the stand must work with little friction and the utmost smoothness.

For work where the wind is strong, on the coast or mountain climbing, it is sometimes necessary to drive a stake into the ground under the camera, and to tie or strap the stand to it, or to suspend

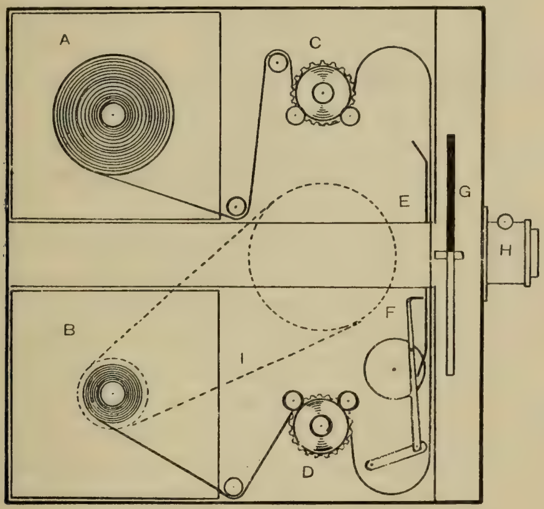


Fig. 3.—Diagram of General Arrangement of Camera

A, Feed-box and roll of unexposed film. B, Take-up box, into which exposed film passes. C, Feed sprocket. D, Take-up sprocket. E, Gate. F, Driving claw (intermittent mechanism). G, Shutter. H, Lens. I, Tension drive.

under the camera a heavy stone or other weight. Firmness and strength are essentials in the stand; means of elevation to a great height are often required; and if these conditions can be fulfilled without making the stand unduly weighty, it is to the benefit of the worker, who often has to rapidly transport his apparatus from place to place to secure satisfactory pictures. A heavy stand is an encumbrance, but an unsteady one cannot be tolerated.

At present most of the work in the studio is done using the folding tripod. In this one respect the kinematograph worker appears to be behind the ordinary photographer, who would scarcely think of using a field tripod in his studio.

The camera contains mechanism by which sixteen successive

picture spaces on the film can be presented to the lens in one second of time. A shutter cuts off the rays of light from the film during the time the portion of film is being moved to bring another portion under the action of the lens. The shutter in the camera obliterates the rays from the lens for about half the total time, and the exposure on the resting film is about $\frac{1}{32}$ of a second.

The same general system obtains in the projecting machine, and a somewhat similar device is used in some printing machines. The three machines differ considerably in detail, but the same principle, i.e. the rapid substitution of a series of somewhat different pictures worked by mechanism of a similar character, is evident in all three. The essential features of the camera mechanism will now be pointed out, and the particular differences and the reasons for these differences stated when dealing with the other machines.

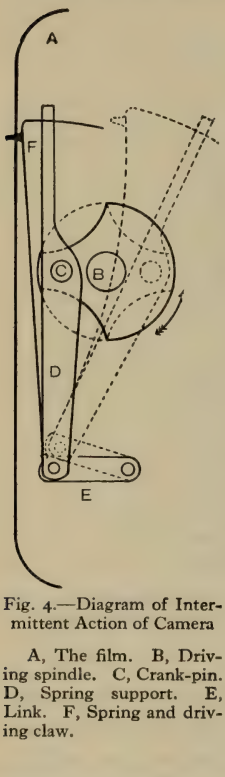


Fig. 4.—Diagram of Intermittent Action of Camera

A, The film. B, Driving spindle. C, Crank-pin. D, Spring support. E, Link. F, Spring and driving claw.

The camera (fig. 3) is a light-tight chamber, fitted with two boxes, the one to contain the unused film and the other to receive the film after exposure. The shutter, which admits or cuts off the light, is usually composed of two discs of thin metal, from each of which a sector has been removed. These are arranged so that by rotating one in relation to the other any amount of the disc up to nearly one-half can be left open. In most modern cameras it is possible to alter the relative position of these plates while the camera mechanism is in action, and thus allow a longer or shorter time of exposure. The shutter rotates between the lens and the film. The intermittent mechanism (fig. 4) which moves the film forward in a succession of jerks differs in various makes of camera. It is essential that the mechanism deal gently with the film, i.e. it must at the start move the film slowly, gradually gain speed, then slow down and leave the film *absolutely at rest* for a time before commencing to again move the film. The longest exposure lasts, say, $\frac{1}{30}$ sec., during which time the film must be quite still, therefore the movement of the film must be effected in about an equal period of time, during which the opaque portion

of the shutter is preventing the light from passing to the film. Before the film reaches the intermittent mechanism it passes over a sprocket-wheel, the teeth of which fit the perforations. This sprocket pulls the film out of the box and delivers it to the intermittent mechanism. It next passes over another sprocket into the receiving box, where it is rewound by a tension-driven roller much like that on the perforator.

The sprockets are called respectively the " feed sprocket " and the " take-up sprocket ", and the boxes are distinguished in the same way.

Early cameras were quite simple compared with those now in general use. The modern camera will operate the film in the opposite direction by turning the handle backwards. This movement was at first only used for making trick pictures in which all motions appeared in their reverse order when thrown on the screen, but it is now an indispensable item, and is used in conjunction with the fade mechanism and for double exposures. Counters which indicate the number of feet of film which has been exposed were in most cameras, but the cameras to-day have quite elaborate indicators by which an individual picture in the series can be brought opposite the lens if desired, no matter how many times the film may have been run through the mechanism or " reversed ". Double, triple, and sometimes quadruple exposures are made on the same film in the production of tricks, visions, and other effects. Another comparatively recent addition to the camera is the " fade " mechanism. This, when set in action, causes one of the shutter discs to rotate slowly in relation to the other, so that the aperture in the shutter slowly closes till no light is admitted to the film. This has the effect of exposing each successive picture to a less extent till no light strikes the film. The effect known as a " fade out " is thus produced. The opposite action—starting with the shutter closed—produces a " fade in ", and a combination of the two actions causes the appearance, now so much used, of one picture fading away and another taking its place, as in the well-known dissolving views.

Another addition to the modern camera is the iris attachment. A rather large iris diaphragm is mounted at some distance in front of the lens. It is adjustable as to distance and position, and by its means the picture can be vignetted or have one side or a part made darker. A holder is also provided into which certain shaped shutters can be fixed and moved as desired, on which cards cut to

shape can be fitted. For quickly substituting one lens for another some cameras have a turn-table in front on which all the lenses are mounted, and any one can be turned rapidly into position.

Special cameras for high-speed work, in which a series of pictures up to the rate of 120 per second have been made, are very useful in the analysis of movements too rapid to be comprehended by the natural eye. When such pictures are projected at the normal rate—16 per second—any movement which originally took place in 1 sec. of time appears on the screen to take eight times as long, and actions quite impossible to distinguish normally can be easily studied.

The management of the camera in the field or in the studio is much the same as when ordinary photography is practised, except that much more care in focusing and more knowledge of the possibilities of minute pictures and of their limitations is required. The user of a kinematograph camera should have an exact knowledge of exposure, should know the laws governing depth of focus, and be familiar with the possibilities of isochromatic screen work, and the actinic value of different kinds of electric illumination. Considerable experience in the use of the different types of lenses is also desirable.

The time of exposure is usually in the neighbourhood of $\frac{1}{32}$ sec., so the amount of light reaching the film is regulated by the lens-iris, and this is often complicated by artificial illumination.

Focusing the picture demands the greatest care, owing to the enlargement to which the finished picture is subjected (sometimes 300 diameters), when want of accuracy such as would be quite unnoticeable in an ordinary photograph becomes unpleasantly evident.

There are several different methods of focusing the picture. (1) By looking at the image on the front of the film itself. (2) By using the film as a focus screen and looking at the transmitted image from the back. (3) By the interposition of a mirror in the path of the light-rays, which being placed at an angle of 45° throws an image on to a finely ground screen that is viewed through a lens. (4) By the substitution in the gate of a piece of matt surface film which acts as an ordinary focus screen. (5) In some cameras provided with turn-tables for the quick changing of lenses, an extra dummy gate is provided and furnished with a fine focusing screen. The lens to be used is turned away from the camera gate over the focus gate, which latter is in exact adjustment with the camera gate. After the lens has been focused, it is turned back to the camera

gate. (6) Most cameras now have focus scales, so that the several lenses can be set to the best position for the delineation of objects at any known distance.

This last-mentioned system is by far the most reliable, provided the mechanism is well made and without shake, and that the scales are accurately marked. Magnifying eyepieces and telescopic sights are also provided to many cameras. These latter are particularly useful in getting visual focus in awkward positions. All lenses should be provided with hoods of such size and length as will prevent the light entering at an angle much greater than is necessary to properly illuminate the picture. Long-focus lenses must have their tubes dull inside, and diaphragms of the proper size to trap extraneous light are a great advantage when the lenses are mounted in long tubes. Telephoto lenses are often particularly useful in kinematography because their mounting is less in length than other lenses giving the same sized images. The finder is also an important item in the construction of a kinematograph camera. The most common form consists of a diminutive camera fixed on the top or side of the apparatus, having its focusing glass always in position, marked to show the different angles of view embraced by the different lenses. For work at a distance the finder is usually sufficiently exact, but when " close-ups "—large heads, &c.—are to be taken the picture must be verified by looking at the image on the film itself. The finder does not exactly agree with the image produced by the camera lens, because it cannot occupy the same place. The nearer the lens of the finder is to the camera lens the more nearly do images agree.

For outdoor work, football, races, or quickly moving objects, the " frame-finder " is the most suitable. This consists of a wire frame somewhere near the front of the camera, and a sighting-point or aperture at the back. Looking from the sighting-point through the frame, the amount of view is at once seen. When arranged for use with several different lenses, the frame-finder is provided with diagonal wires furnished with hooks over which an elastic band can be placed, limiting the view according to the angle of the lens in use.

The particular advantage of the frame-finder lies in the fact that a moving object can be seen before it enters the field of the camera; the operator can consequently know when the critical event is going to take place. For telephoto work with long-focus lenses, a telescope provided with cross wires in the eyepiece, and with means of adjusting its axis to the axis of the lens is required.

Finders should be checked for accuracy frequently. The finder is the " sight " of the camera—it is no good to fire a gun with incorrect sights.

The " gate " of the camera claims careful attention. It is designed to hold the film flat and steady during the time of exposure, and is provided with a spring-pressed plate. This must be kept clean, as also must the surface against which the film is pressed. Some cameras have also an arrangement to press on the edge of the film to prevent side movement. The springs which cause these pressures are often adjustable, and should be kept at such a tension that they just steady the film when the machine is run at its normal rate. Pressure greater than the required amount causes the machine to drive heavily, and may produce scratches on the film. New film is often soft and inclined to adhere to the gate surfaces. A very slight smear of tallow or oil on these surfaces will counteract this tendency.

The film-boxes should be light-tight when out of the camera. In many boxes the film passes in or out through a mouth lined with velvet, which should be examined from time to time, and cleaned from any accumulation of dust.

Some cameras automatically open the mouths of the boxes before the camera is used, and close them before the camera can be opened. This system has the advantage of doing away with the rubbing of the velvet on the celluloid when the film is passing. Under some conditions of atmosphere the slightest friction on the film caused by a non-metallic substance is liable to develop static electricity. Gate pressure-pads should be of metal; velvet and other non-metallic substances should be rigidly excluded.

The " take-up tension " allows the roll of film in the box to rotate more and more slowly as it increases in diameter. Usually the tension arrangements are part of the camera mechanism, but in one or two cameras the tension device is located in the film-box. The tension should be sufficiently powerful to decidedly roll up the length of film; any extra tension tends to wear out the mechanism and causes the camera to drive heavily. Special attention should be devoted to the adjustment of the tension device, neglect of which has probably caused more breakdowns and consequent waste of valuable film than have all the other defects and troubles common to camera operating.

The camera should run lightly. Any extra pressure in turning the handle may cause the stand to deflect, and unsteady pictures

will certainly be the result of heavy driving. When attaching the starting end of the film to the spool in the take-up box, be sure to take up any slack, as most cameras are liable to jam or for the film to become detached from the spool if this point be not attended to.

Cameras differ so much in design that only general directions can be given for their use. Instructions supplied by the makers should be carefully studied, and some spoiled film passed through the camera before trying serious work.

The Development of Kinematograph Film.—Film is developed in complete lengths of about 400 ft. when it has had an even exposure, but it often happens that part of the roll has been used for quite a different style of picture from that of the remainder, and requires different treatment in development. The ends of the different subjects having been marked by a punch in the camera, suitable sections are selected and pinned together till there is enough to fill a frame. The development of a 400-ft. length of film requires special appliances. Perhaps the most general method is that of winding the exposed film round a series of brass pegs supported on a skeleton frame, also of brass. The roll of film is held in one hand and wound on the pegs by the other hand, beginning at the centre and continuing outwards. The loaded frame is then placed horizontally in a trough which it nearly fits, and which contains enough developer to cover the film. The frame is lifted out from time to time to watch the progress of the development, and is then transferred to a similar trough containing water, and then to another for fixing. For the final washing the frames are placed upright in a tank large enough to contain several; water flows in at one end and out at the other end. Washing is thus complete and rapid.

The films are usually dried on a wooden drum like a large squirrel cage, which is kept revolving. Warm dry air is forced through the room in which several of these drums are operated.

Frame development has many variations; upright frames in upright troughs and long wood frames in rocking troughs have been used, but the general principle is the same in all.

Mechanical development is now gaining ground, and bids fair to become the standard method.

Two distinct systems are in use, one in which the film is drawn through a series of long shallow troughs at such a rate as to ensure its complete development and fixation, and another in which upright tubes of liquid take the place of the long shallow troughs.

Films are often dyed or tinted after development by placing

them, while still on the frames, in tanks containing the necessary solutions. The mechanical system also lends itself to this purpose, extra troughs or tubes being added to the machine.

The tube system possesses several advantages over the trough method. The small amount of solution in contact with the air saves oxidation, and sediment can be drawn off from the lower ends of the tubes without interfering with the operation of the machine.

When pictures are taken in the tropics, or far away from civilization, it is often necessary to develop the film soon after its exposure. Portable troughs arranged to pack in nests, containing brass skeleton frames, are usually carried. Difficulty is sometimes found in getting a supply of water sufficiently pure, and also in keeping the temperature down so as not to " frill " the film and cause it to come away from the celluloid support. In cold situations it is often difficult to keep the solutions warm enough to work satisfactorily. Solutions for developing, fixing, and the water for washing films should be kept at near the same temperature; sudden change may cause the picture to frill. These precautions are only necessary in extreme conditions of temperature.

The positive film is developed much in the same manner as is the negative, the developing solutions being varied to produce the best results according to the particular make of film and the subject. The negative emulsion is much like that of a dry plate, while the positive is more of the quality of a lantern plate.

The Printing Machine.—The finished negative has now to be printed on to the positive film, and for this purpose a machine is required. The positive film is less sensitive to light than is the negative, so more light can be used in the dark room during its manipulation.

The printing mechanism (fig. 5) is to an extent similar to that in the camera, but it has to deal with two films instead of one, and has to keep them closely in contact, and it also has to exactly superpose their respective perforations. There are two distinct systems by which prints are made from the negative—the " step-by-step " system and the " rotary ".

The intermittent mechanism of the step-by-step machine is much like that in the camera, and a somewhat similar shutter acts to cut off the printing light during the movement of the film. One picture is printed at a time, the rate of the machine being governed by the power of the printing light, the density of the negative, and the photographic rapidity of the film. The operator watches the

negative as it passes through the gate of the machine, and if the density changes, or if the subject alters much, compensates the change by moving the printing light nearer to or farther from the film when necessary. Some printers are provided with means of rolling up the films after they have passed through the machine,

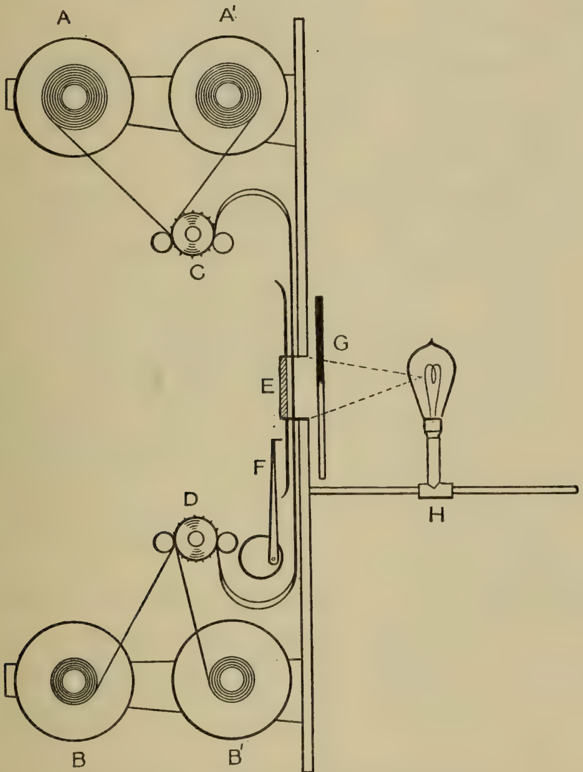


Fig. 5.—Diagram of Printing Machine

A, Unexposed positive film. A′, Negative film. B, Positive take-up. B′, Negative take-up. C, Feed sprocket. D, Take-up sprocket. E, Gate and pressure-pad. F, Claw (intermittent movement). G, Shutter. H, Printing light on slide.

but often they are allowed to fall into a deep box, and are afterwards wound by hand.

A mask of the exact size of the finished picture allows the light to act only on the part of the film being printed, and this mask is movable up and down in order to enable the operator to adjust it in agreement with the picture space.

Recently many improvements have been made in the machines

and the methods of producing prints. The speed at which the prints are produced has been much increased, and it is possible with recent machines to produce a number of pictures from the same negative, all of the same quality and density. With the above described methods this was difficult if not impossible, because the expertness of the operator was the only governing factor in the exposure. In the rotary system the films are drawn continuously past a slot. A powerful illuminant acts on the film, and the amount of exposure depends upon the speed of the machine and the width of the light-admitting slot, which can be varied.

According to the density of the negative, the slot requires to be made wider or narrower from time to time as different sections pass through the machine. This alteration of light intensity is effected automatically in the most modern printing machines. The edge of the negative film at a point near the printing slot is pressed by a spring lever. Certain nicks in the film edge are arranged to allow the lever to fall into them as they pass, and the number of oscillations imparted to the lever cause the necessary alteration in the width of the slot. In determining the necessary light alterations, a trial print is first made, the light changes being carefully noted. If on projecting the picture the exposure is considered to have been correct, the necessary nicks are cut in the edge of the negative, which can then be printed almost automatically, with certainty as to the evenness of the prints produced.

A similar arrangement is sometimes applied to the step-by-step printers, but in these the variation in the power of the printing light is effected by introducing more or less resistance into the lamp circuit.

The rotary printer has no shutter, and as its action is continuous it can be run at a much increased speed, which is limited only by the intensity of the light source. The light itself does not need to be varied, its effective amount being adjusted by the slot width.

The difficult problem in printing machines—a mechanical one—is the keeping of the two films in actual contact, and also exactly superposing the perforations. When the positive and negative perforations do not quite agree in gauge, very little difficulty is found in the step-by-step system, because each picture is automatically adjusted afresh while the light is cut off by the shutter.

The rotary machine requires that the perforations in the two films be accurately matched; if not, a slight shift takes place as each

sprocket tooth enters and leaves the perforations, and when this occurs the prints will be slightly blurred.

The difficulty of keeping exact contact between the films has been approached in several ways. The most certain method employs air pressure for the purpose, either in the form of a chamber behind the picture space supplied with air under slight compression, or by a jet or jets of air arranged to blow the two films together.

The Projector.—We now come to the final apparatus by which

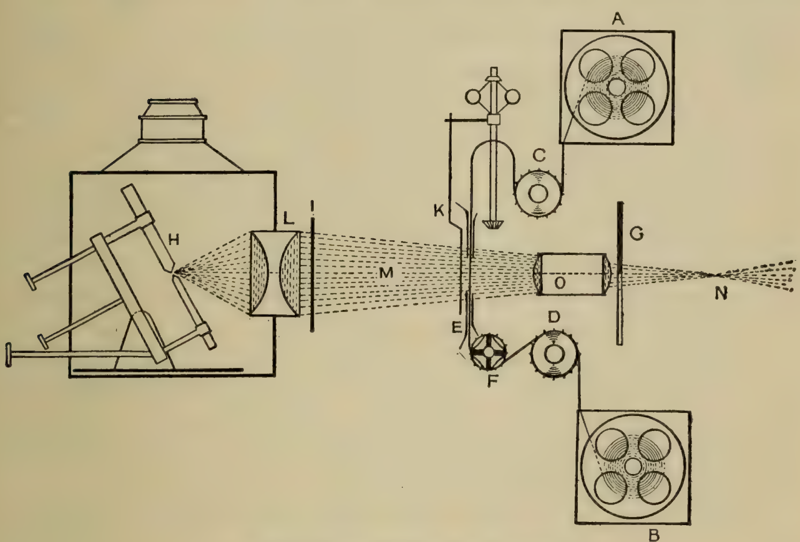


Fig. 6.—Diagram of Projecting Machine

A, Film-box (feed). B, Film-box (take-up). C, Feed sprocket. D, Take-up sprocket. E, Gate. F, Intermittent action (Maltese cross). G, Shutter. H, Arc-lamp. I, Hand-operated safety shutter. K, Automatic safety shutter. L, Condenser. M, Path of light-rays from condenser. N, Virtual crossing-point of rays. O, Projection lens.

a highly magnified image of the positive picture is projected on the screen.

It consists of a lantern or " lamp-house ", an optical system, and the mechanism for moving the film. The optical system is similar to that of the ordinary optical lantern for glass slides. Lime-light is occasionally employed, but where electricity is available an arc light is always used.

Whatever light be used it must be powerful, and will of necessity be accompanied by a considerable amount of heat. The film picture being small (1 in. by $\frac{3}{4}$ in.), all the light which reaches the screen, and its accompanying heat, must pass through this small area of

celluloid. Normally each picture is subjected to the light and heat for somewhat less than $\frac{1}{16}$ sec., but should the mechanism stop, the film break, or for any reason fail to move forward, ignition will take place in a more or less short time, according to the power of the light and the heated condition of the gate of the machine.

The projector mechanism (fig. 6) follows the same general idea as that of the camera. Two spools, contained in boxes, an intermittent mechanism, two sprockets, a spring gate, and a revolving shutter are the essentials. The film-boxes are large, each capable of containing from 1000 to 2000 ft. They are constructed of fire-proof material, and provided with mouths which, while allowing the film to pass freely, will prevent flame from entering the box. Brass rollers, or long surfaces of cold metal in close proximity to the film, are among the devices employed. The gate has also such surfaces, and should the film become ignited in the gate aperture, the flame should not travel either up or down. An automatic shutter which falls and cuts off the light and heat when the machine stops is also a necessary adjunct. There is also another shutter, operated by hand, for the same purpose. There is an unfortunate liability in all automatic safety appliances to fail to act just at the time when action is most required. The hand device cuts off the light irrespective of the action of the machine. All the foregoing items are demanded by the authorities before a machine is allowed to be used for a public performance.

Many forms of projector have been used since the first days, variations in the construction of the intermittent mechanism being the most noticeable feature. This part now nearly always consists of an intermittently rotated sprocket, small in size and light in weight, to minimize as much as possible the effects of inertia and momentum. The film is pressed against this sprocket by spring guides, and the intermittent action is produced by the Maltese-cross gear (fig. 7) well known to mechanics. The gate in the projector is provided with a spring pressure-pad—as in the camera—to flatten the film and to steady it against overrunning. The same precautions must be observed in the projector gate as in that of the camera, but as the projector gate becomes heated, extra care against the tendency of the gelatine to impact on the sliding surfaces must be exercised. When using new film for the first few times, a minute amount of vaseline or other similar lubricant must be frequently applied to the parts past which the film slides, and they must be often examined and cleaned. A considerable amount of knowledge and experience

must be possessed by the operator in projecting, say, a 60-ft. picture. It is at times necessary to act with decision, without the loss of a second of time, in order not to interrupt the even run of the programme.

The mechanism—usually driven by hand—is sometimes operated by an electric motor, the speed being regulated by a resistance. The shutter is usually placed beyond the front of the projecting lens, at which position the light-rays occupy the smallest space. The shutter differs from that of the camera and printer in having three blades, one to obscure the light while the picture is changed, and

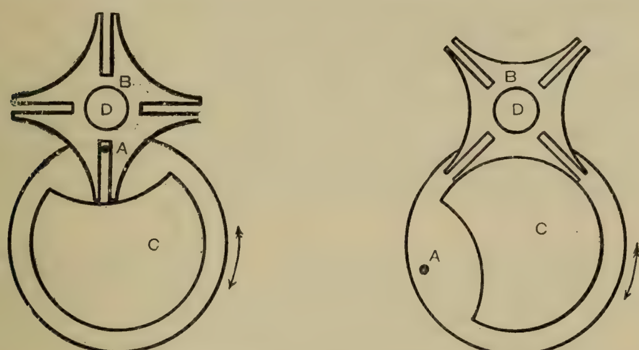


Fig. 7.—Diagram of Maltese-cross Action

On the left is shown pin A driving the cross B. On the right is shown cross B at rest and held in position by locking-plate C. The intermittently-moved sprocket is fixed on the spindle D, to which the cross B is also fixed.

two others which pass while the picture is at rest for the purpose of suppressing " flicker ", as will be explained later.

The optical system has a condenser just like an optical lantern, but the projecting lens is about one-third of the focus. The film, instead of being close up to the condenser, is at a distance where the cone of rays from the condenser well covers the corners of the film picture. This separation of the picture from the condenser is the cause of some difficulty in evenly lighting the screen. Lenses, such as are used in condensers, suffer from spherical aberration, i.e. they do not deflect all the rays to the required amount to produce an exact focus, the outer rays being bent too much to allow them to cross the same point as those from the centre of the lens; in consequence, the cone of light is unevenly concentrated. Alteration of the cone of light by moving the arc-lamp alters the relative amounts of light passing through different parts of the picture, and by a

few trials an arrangement of the several items can be found where the screen is strongly and, at the same time, fairly evenly illuminated. To facilitate these adjustments the projecting lens is movable with respect to the film, the arc-lamp to the condenser, and the lamp-house with respect to the film.

Near the condenser—sometimes between it and the arc-light—is the hand-operated shutter, by which all the light (and heat) can be shut off from the film. The automatic shutter is usually just next to the gate on the condenser side. It is operated by mechanism connected with the machine, and is so arranged that when the machine has attained a speed of, say, 10 pictures per second, it rises and allows light to pass. Should the speed fall much below this, the shutter closes and cuts off light and heat from the slowly moving film.

The arc-lamp is supplied with mechanism by which the carbons can be placed in any desired position. It depends for its result upon the skill of the operator. It is hand-fed, centred, and adjusted; the operator requires considerable experience to attain the best result.

The take-up spool in the projector is driven by a tension like that of the camera, but of much stronger design. Instead of 400 ft., it may have to deal with 2000 ft., which must be wound with certainty, as any slack film in proximity to the arc-lamp or to the concentrated light from the condenser constitutes a source of danger. The tension must be so adjusted that while being sufficiently powerful to roll the film when the spool is full, it is not strong enough to tear the perforations in the film as it passes over the take-up sprocket.

Motor-driven projectors require the operator to be watchful and alert. Film may be brittle with long use, or a join may give way due to an overtight tension. The operator must always be ready to shut off the light, and rectify any accidental occurrence.

Before leaving the subject, it may be well to glance at the physiological aspect of the science of kinematography. Had this side of the problem been understood in the first days, progress would have been much more rapid. Many of the facts were well known but not realized as applying to the subject. Experiments gradually improved the results till perfection was attained, but the reasons of the improvement were often not understood.

In the camera only one-half (generally somewhat less) of the movement of an object is recorded because the shutter obliterates the remainder of the movement. In the case of a small object moving across the picture at a high speed, no distinct rendering will

be found on the developed negative. The distance moved during each exposure will be represented by a blur, the length of which will be equal to the amount of space passed through by the object in about $\frac{1}{32}$ of a second. As the object moves while the shutter acts, the blur on the succeeding picture will be separated from the previous position by a blank space. When projected, a series of blurs, each separated by a space from the next one, will appear on the screen. A flying bird or a tennis ball is very inadequately reproduced. It might be supposed that so poor a record of the original could not give satisfaction, but as the eye views such a subject in nature it cannot distinguish details, nor can it hope to do so on the screen. As the eye follows the apparent movement of the object, the stronger part of the blurred images—the middle portions—impress themselves on the retina, and more or less remain and bridge over the spaces, and to an extent give the impression of continuity. The longer the shutter remains open compared with its obliteration period, the longer in proportion will the blurs be and the shorter the spaces, and vice versa.

It is doubtful whether any advantage would be gained by increasing the time of exposure to more than half. If the blurs could be made to join one another, owing to the persistence of vision, the appearance on the screen would be that of a blur more pronounced and longer in proportion.

In the first days, movements of persons and things were rendered on the screen in a jerky manner. This was greatly due to a false idea —a desire on the part of the photographer to secure sharp pictures. In order to do this he reduced the opening of his shutter and recorded less than one-fourth of the total movement of the object. On projecting the picture, say of a moving ball so photographed, the appearance on the screen would not simulate the movement of one ball but present a string of balls, each one stationary, the first and last of the series faint, and the middle one well defined. The last of the series would disappear and others appear in front, each becoming stronger and fading in succession. With strong contrast perhaps six to eight images could be seen at a time. An image of a quick-moving limb appeared as if the owner was temporarily supplied with two or more, and the wheels of vehicles revolved in the wrong direction or not at all, as often as not.

Animated pictures for a long time were much marred by flicker; the 16 per second flashes of light were painfully evident. Many devices were tried with the idea of curing the defect. It has been

found that the eye cannot appreciate the intermittence of light and darkness, provided the changes take place at a greater rate than about 40 per second. By putting two extra blades on the projector shutter 48 obliterations take place in 1 sec., and to the eye the light appears quite continuous. One thing, however, is of great importance—the obliterations must be of equal length, and quite equally spaced; if not, a certain amount of flicker will be evident.

The three-bladed shutter cuts off just about one-half the light, each blade being about one-sixth of a circle; the change of picture takes place in a little over $\frac{1}{100}$ of a second, while one of the blades is passing. The loss of light is certainly great, and has to be made up by increase of electric power.

In order to produce the best effect on the screen, the room should be dark—the darker the better. All objects surrounding the screen should be dark in colour and dull in texture. Any light entering the eye at a greater angle than is subtended by the picture falls on a part of the retina more sensitive than the centre part occupied by the picture, making the screen appear less bright, and any fluctuation in the light will be much exaggerated. It should be the aim of the exhibitor to provide a well-lighted screen with the smallest expenditure of electric power, and by using less light (and heat) to conserve the durability of the film and minimize the danger of fire.

CHAPTER XIV

The Camera as Witness and Detective

In many instances photographs may be used in the interests of justice, to demonstrate to magistrate or to judge and jury various points about which there is no question, such as the position of a turning, street-refuge, or curb-stone, so that in the mind's eye the scene, say of an accident, may be rightly reconstructed. They may also be of particular value when taken for the purpose of making clear what were the facts at a certain time, which might afterwards be disputed in court. For example, a farmer might claim that the death of an animal was due to an attack on it made by one belonging to a neighbour. In this instance a photograph could well show that the condition of the claimant's hedges permitted the encounter, and that he had only himself to blame. Again, a photograph or a series of pictures taken for quite another reason, such as a film showing a prize-fight, may on occasion settle a dispute as to the action of one or both of the combatants.

Photographs may in other, and especially technical, cases afford valuable evidence, especially in corroboration of the expert who wishes to show the transitory results of a test which he has had to make. Furthermore, owing to the fact that sensitized plates are able to record and emphasize differences of tint that are not appreciated by the human eye, and lenses to render details visible which unaided by the microscope it could not see, the camera at times assumes the rôle of detective as well as of witness.

The present writer has had some little experience in connection with ink writing which has been deleted from documents by chemical means, with the object, of course, of replacing it by other words which may enable the possessor to reap some pecuniary or other advantage in a nefarious way. Where the work is done well, nothing will be noticeable; but all the same, when the ink contains iron, as

it customarily does, there may be a yellow trace so faint as to be invisible, but still a trace, where the original writing was.

Yellow light has, like red, very little action on ordinary slow plates, and this is why when a photographic image which has faded and turned yellow is copied by means of one of these, it is often much improved. Where the yellow fell on the plate the negative is transparent (for the silver was altered but little and dissolved away in a fixing process), while the positive consequently is dark. Similarly, the yellowish ink traces appear once more as writing in the photographic print.

In fig. 1 the letter "A" is the first initial of a name which the camera revealed had been removed from a postal order and replaced by a "J", which is also shown. This, as is to be expected, is much blacker.

Where it is inadvisable to apply reagents to a document, the original writing may be brought up by photographic means alone, as in the illustration just mentioned and in fig. 2 (p. 506). In such cases it is important to get as actinic a light as possible, and the writer has found particularly effective that which is produced by burning magnesium ribbon. When it is allowable to experiment, the surface of the paper may be damped with a solution which will darken the iron of the bleached ink if it is present. It then becomes visible to the eye, for a time at least, and there is a chance of obtaining a good photograph with greater ease.

We may describe and illustrate one or two cases. They are in connection with Russian internal passports, which were issued to enable their holders to move from place to place in their own country. These are small books, and the pages on which the various details are entered have engraved backgrounds, intended, no doubt, as a safeguard against erasure. While the destruction to the pattern would be the result of ordinary scratching out (see fig. 3), the printing is unaffected in the case of chemical deletion and rather helps than hinders the forger, for it tends to obscure any trace of his work that he may leave behind him.

Previous to the War, numbers of Russian subjects had taken refuge in this country. They had with difficulty in many cases escaped from their own. Their plan was first of all to obtain an internal passport which enabled them to enter a district abutting on the frontier, over which they managed to slip in ways that they preferred to keep to themselves.

It may be well imagined that when the combat was raging, the

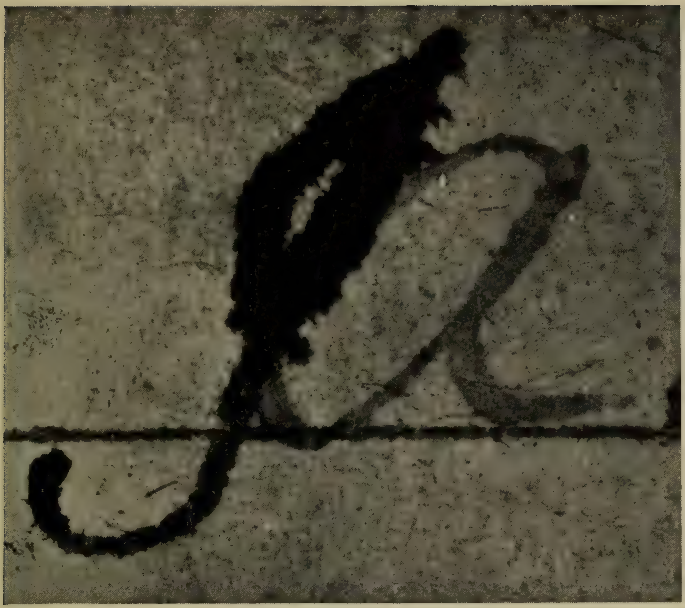


Fig. 1.—The capital "A" from the name originally written on a postal order, brought up by photography under the initial "J" of another name substituted for it after chemical deletion.

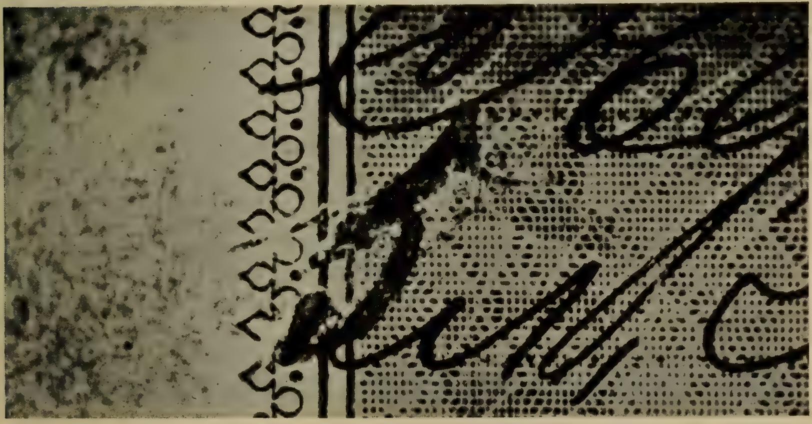


Fig. 3.—Part of Russian passport showing where the engraved background has been destroyed by scratching out parts of a figure previous to its alteration into a "5"

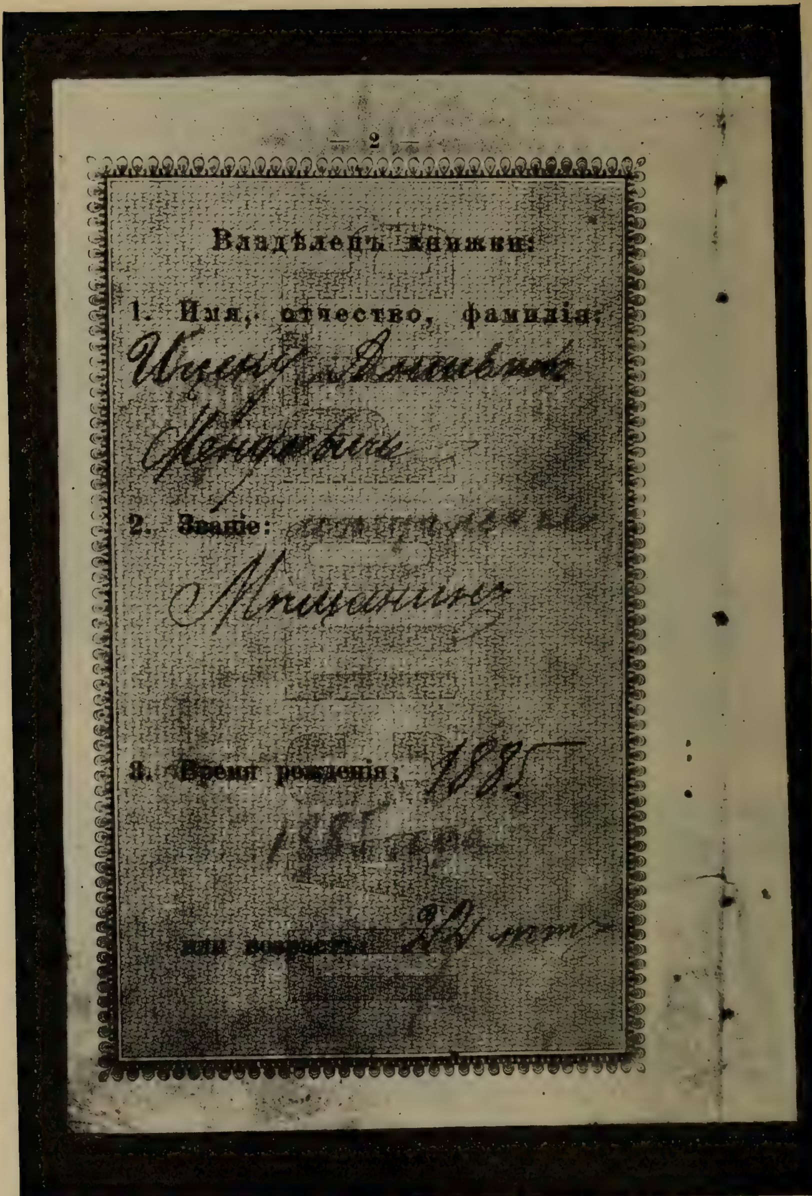


Fig. 2.—Original entries on the second page of a Russian internal passport brought up by photography alone

(By the courtesy of *The Whitehall Gazette*)

Russians over here had little wish to leave their families and go back to fight for the country in which they had suffered. A number of them of military age also preferred to avoid, if possible, the other alternative of enlisting in the British army.

Here a Russian passport belonging to themselves, or for that matter to someone else, came in useful, for it could be altered to show that the holder was over military age and had duly served his time in the Russian army.

To remove and replace a few words or figures would not be easy to do without arousing suspicion, for differences between the colour of the new and old ink and in the style of the original and substituted writing would be difficult to hide. So every bit of writing on all the pages except that bearing the signatures of the officials who originally issued the passport was removed, and entirely new entries as to date of birth, military service, personal appearance, and whether the holder were married or not were put into the passport instead.

Merely by photography, though usually with the help of suitable reagents, parts of the old writing were brought up sufficiently to show that the document was a forgery. Often the original entries could be read without difficulty by anyone who knew Russian, and the dates written in ordinary figures by those who did not. Fig. 4 is from a passport issued to a man who was born in 1877 as shown by the figures brought up, whereas the date alone appearing to the eye before this had been done was 1870. Similarly, while his term of military service ended in 1899, the date had been put back seven years also, as it read " 1892 ". This is very evident in the next illustration (fig. 5).

It was very disconcerting to the solicitors and counsel who had to defend men accused of using such forged documents to be confronted with photographs of the original entries.

Again, a man was finely caught who swore that a passport was issued to him in which on the page relating to marriage the words " no husband " were found, indicating that the book had originally been filled in in favour of a single woman (see fig. 6).

One of the most interesting examples met with was an external passport which allowed the holder to leave Russia in the proper straightforward way. In this on various pages, in several different languages, permission was given to Mr. Abram Brilliantenstein to travel abroad. Tests applied to the page printed in German characters showed, nevertheless, that it was originally issued to a woman, for she was said to be accompanied by her daughter and her maid-

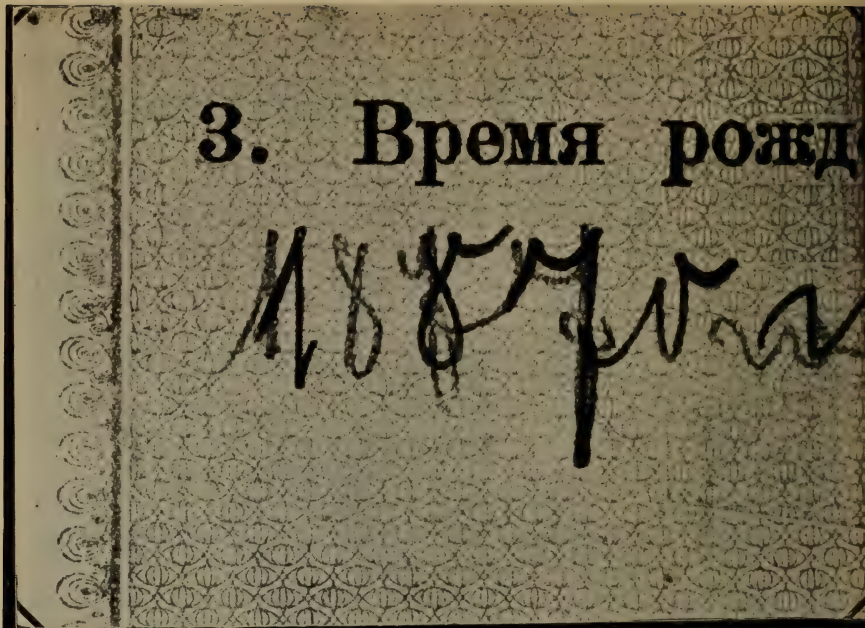


Fig. 4.—Date of birth originally written " 1877 " made to appear as " 1870 "

(By the courtesy of *The Whitehall Gazette*)

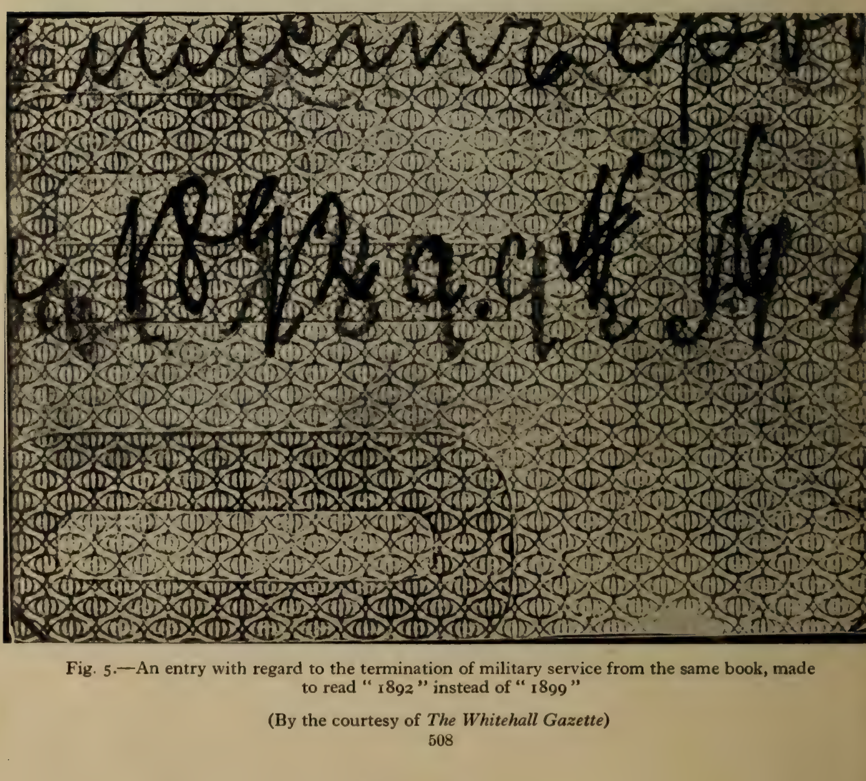


Fig. 5.—An entry with regard to the termination of military service from the same book, made to read " 1892 " instead of " 1899 "

(By the courtesy of *The Whitehall Gazette*)

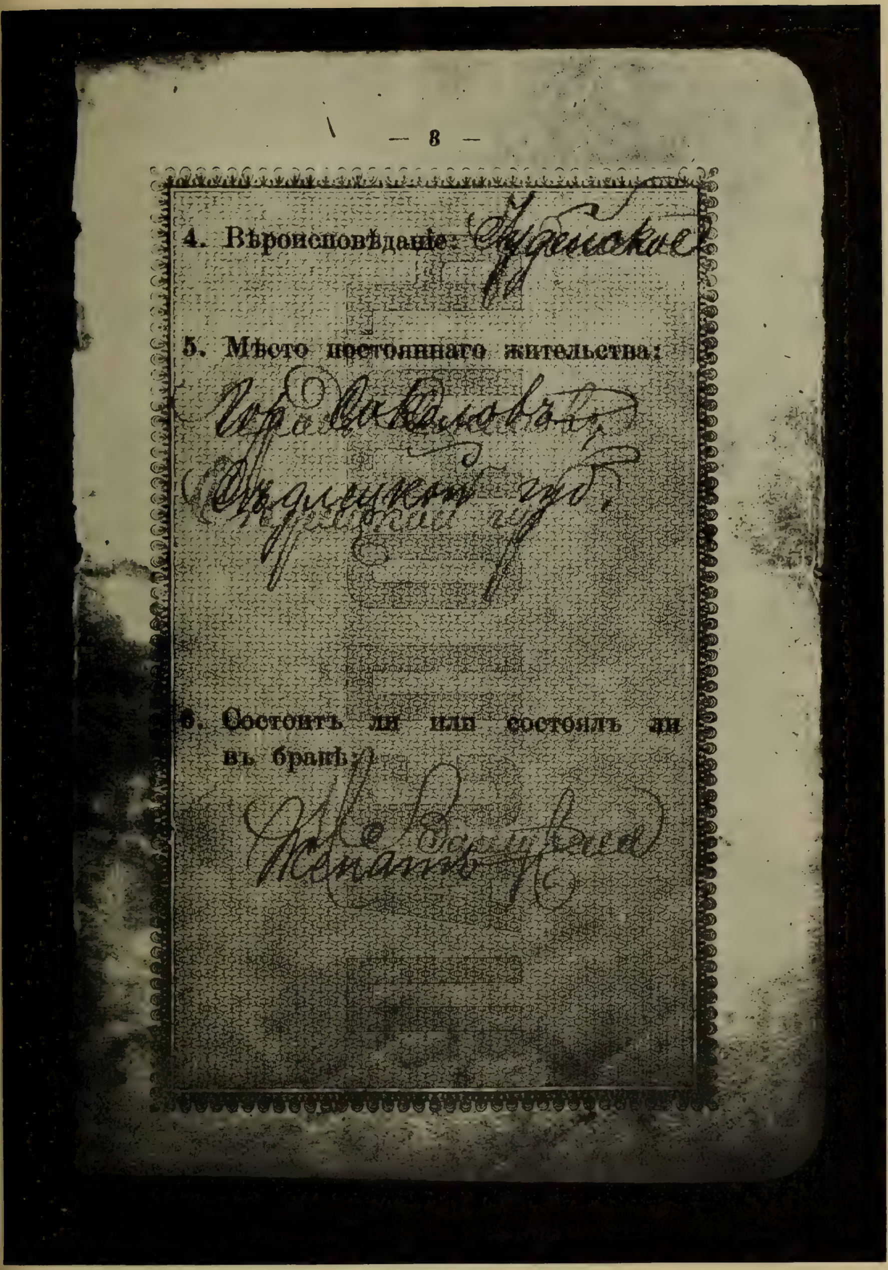


Fig 6.—Page 3 of a passport presented by a man and stating under paragraph No. 6 that he was unmarried. Above this, however, the words indicating "No husband" have been brought up, showing that the document was originally issued to a woman.

(By the courtesy of *The Whitehall Gazette*)

servant. In the space not covered by the new writing in fig. 7 the name of the latter, "Estere Blumental", preceded by the word "Dienstmädchen" (maidservant) and followed by "reisen ins Ausland" (travel abroad) can clearly be made out.

As was usually the case, the old writing of the owner's name was very much mixed up with the ostensible entry giving that of the new one. Photography, however, was able to play a part in its elucidation. A transparency was made of the portion of the page concerned, and an image of it thrown by an optical lantern on to a large sheet of white paper. Then the lines of the original name where they were visible were traced over with charcoal, and connections also added where they disappeared under the new writing. Afterwards, when the sheet of paper was examined in daylight, the name "Millie Klauser" was easily read. This lady was the mother-in-law of the man who presented the passport. Though an attempt was made to show that this was not the right spelling of her name, it tallied exactly, however, with that of a signature, which she had added to a statement made by her in conjunction with Brilliantenstein that the passport was his, that was afterwards discovered in the back of the latter. Nothing more was necessary to show that she had given it to him and that it had been altered for his benefit.

Sometimes the work of deletion was not done so well as at others, and traces were visible to the practised eye, or the size had been removed to such an extent from the paper that the new ink ran. Figs. 8 and 9 show reproductions of photographs, taken bigger than the original writing, of a piece of the signature of the issuing officer which had not been tampered with, and that of the new owner of the passport. In the first case the edges of the lines are sharp, but in the second, though the marks of the pen are distinct, the ink has spread beyond them and run into the paper.

At times, to prevent this running, the size was replaced with other material, and this had to be painted on to the page. If this work was not done thoroughly, when the passport was held at a certain angle, light was reflected from the parts which had been painted and not from the others, so that this could be shown in a photograph (see fig. 10).

On one occasion a passport was found to have been made up of parts of two others. The edges of such documents were cut flush with the cover after they were bound, but, as will be seen from fig. 11—in the case under consideration—some projected slightly beyond the others, and enlargements of the engraved backgrounds

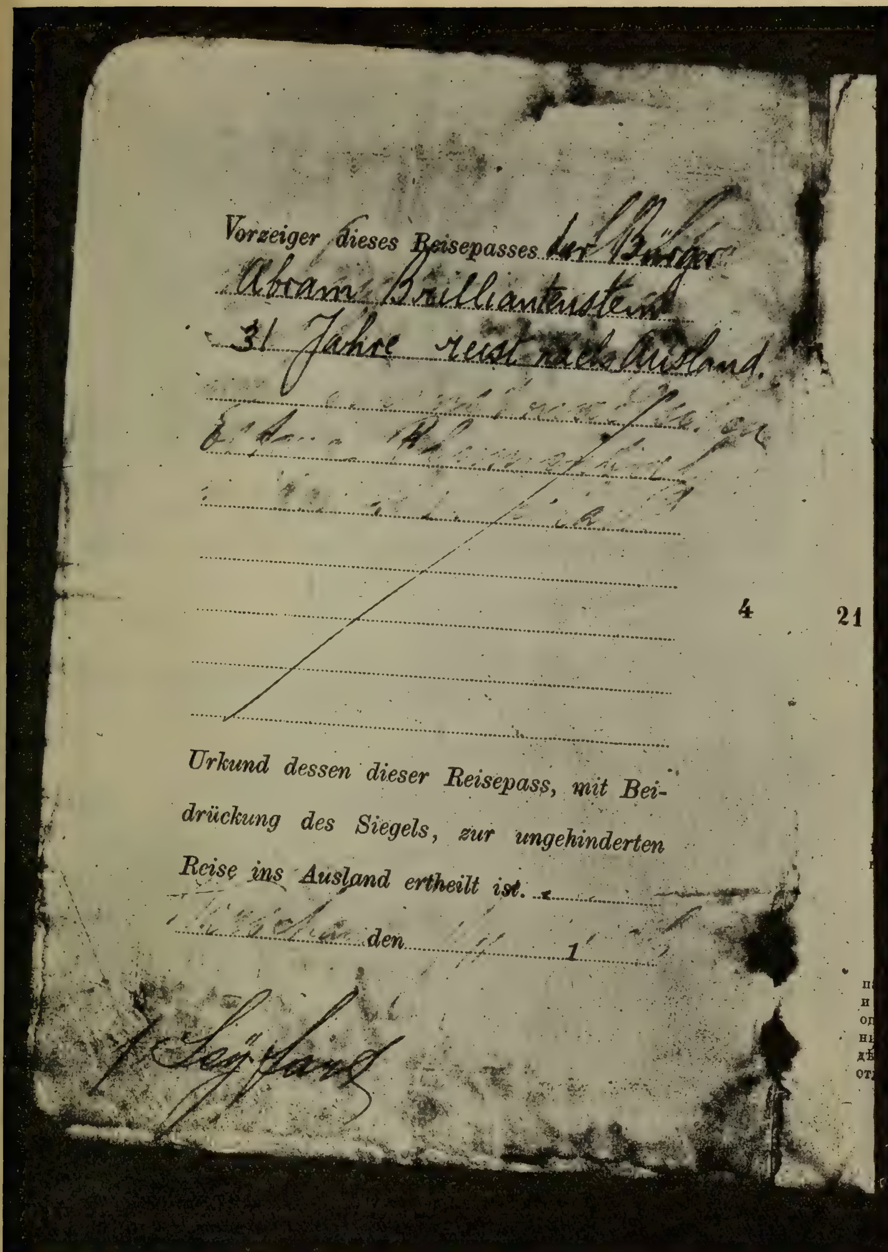


Fig. 7.—A page from an external Russian passport apparently belonging to a man, but which, as the original entries show, was really in favour of his mother-in-law, her daughter, and her maid-servant.

(By the courtesy of *The Whitehall Gazette*)

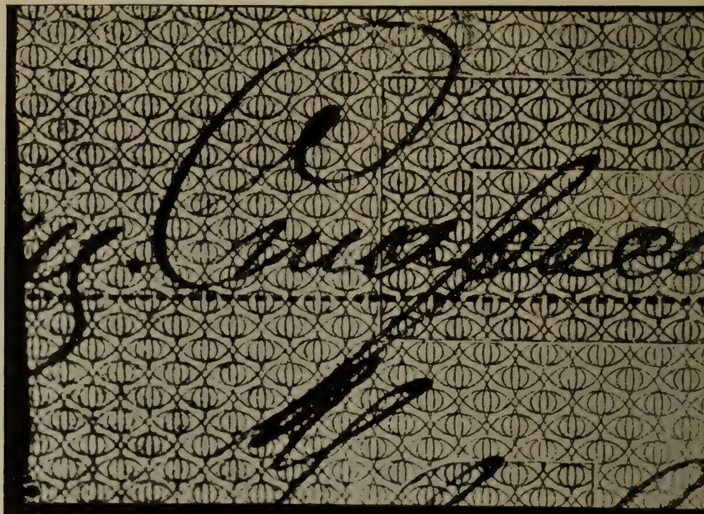


Fig. 8.—Part of the signature of the officer who issued the passport, showing the sharp edges of writing on paper which has not been tampered with

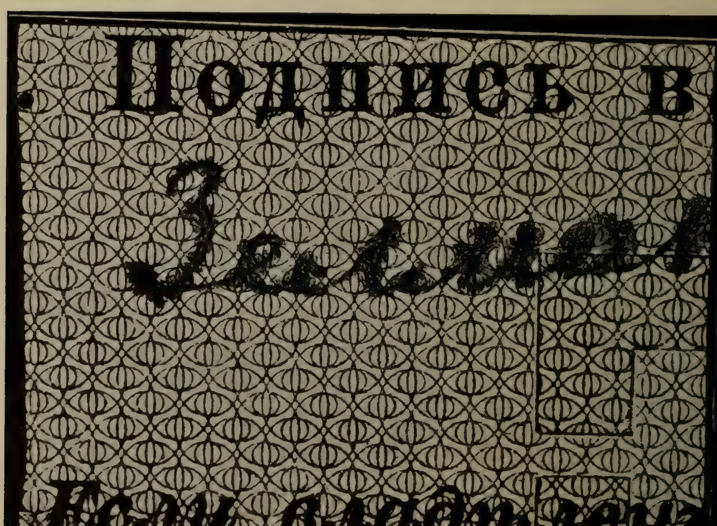


Fig. 9.—The signature of the new owner of the same passport written in the space from which the previous name has been deleted by chemical means. It shows how, on account of the size having been removed from the paper, the ink has run and the edges of the writing are irregular.

(By the courtesy of *The Whitehall Gazette*)

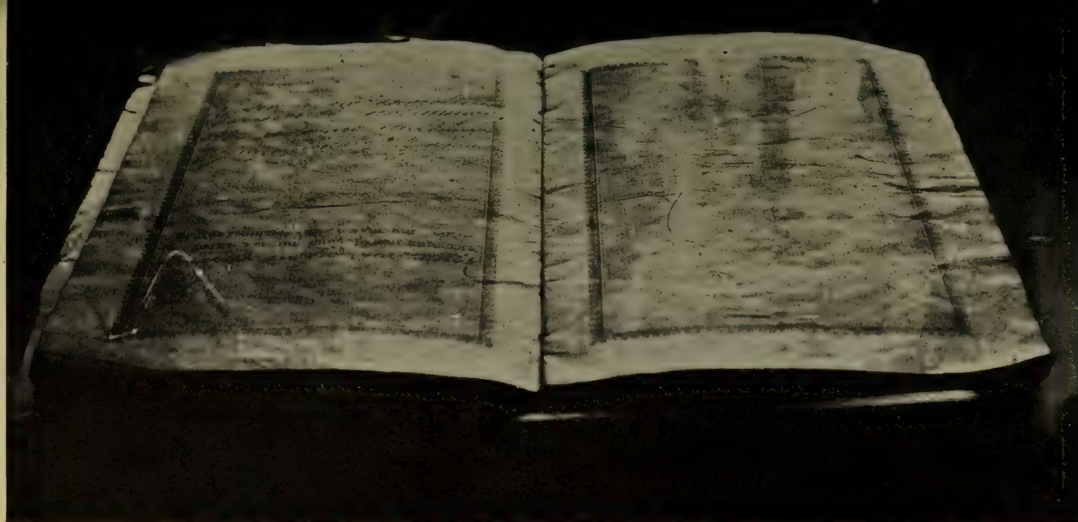


Fig. 10.—A passport on which the pages have been partly covered by material intended to replace the size and to prevent the ink from running. The light is reflected from the covered parts, but those which were missed appear darker

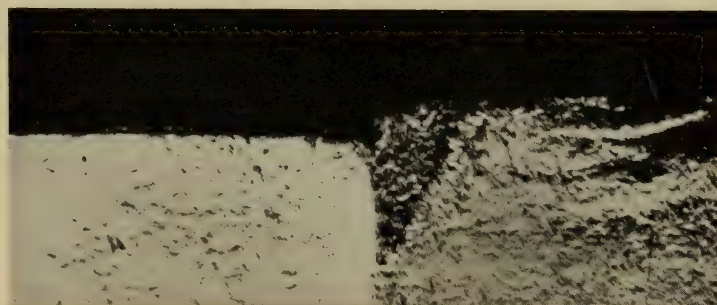


Fig. 11.—A photomicrograph showing part of a passport made up of two old ones

showed also that those on the smaller pages were somewhat different from those on the others.

The climax was reached when a passport was examined which was proved to have been used by at least four individuals. There were the visible entries referring to the man who presented it, and three other series which were brought up and photographed. Fig. 12 shows the leaf numbered 8 as it appeared when presented, and indicating that the owner was unmarried. For comparison the same page is shown after treatment (fig. 13), when it was found that two of the original bearers had children, and names of these and the dates of their birth were given. The fourth man concerned was apparently again a bachelor.

The number of these falsified passports was such that it was perfectly evident that somewhere in London quite a business was made of producing them, though who actually carried out the work it was never discovered.

In the forgeries that we have dealt with the need for imitating any particular person's writing was obviated by leaving the issuers' signatures untouched. Where there is a question of this having been done, lenses such as that used to produce the spread signature (fig. 9) come in useful for producing magnified photographs, and these, if the writing has been carefully copied, may show signs of hesitation—such as lines which are not firm or freely written, shakiness or slowness, or, again, lifts of the pen where these are not customarily made by the person whose writing has been imitated. On the other hand, the absence of any of these blemishes and an appearance indicating steadiness and speed go to show that the writing is genuine, or is the result of long practice or exceptional skill on the part of the forger.

Genuine signatures vary, and mathematicians have calculated the immense odds against the series of strokes which form them occupying exactly the same positions in two examples. If, therefore, a disputed signature and a genuine one are very much alike, this in itself is a ground for suspicion, and points to the doubtful one having been traced from the other. Fig. 14 shows a genuine signature quickly and freely written; fig. 15 is very much like it, but it has been slowly and carefully produced, and looks more as if the writing had been made in a copybook. The distances between the important strokes will be found on measurement to be practically identical in both cases, as are the relative positions of the contractions "Hon. Sec." which follow the signatures, with regard

to them and to each other. A point to be noted also is that in the second case the contractions are so close to the bottom of the cheque that they could not have been written at all comfortably. Their position looks abnormal, and, as a matter of fact, on a large series of genuine cheques which were examined, in no case were they anything like so low down.

The result of superimposing one cheque upon the other and photographing the two with the light behind them is shown in the third illustration of the series (fig. 16), and it will be seen that, except for a few details where the outline has not been successfully followed, the signatures and the contractions agree.

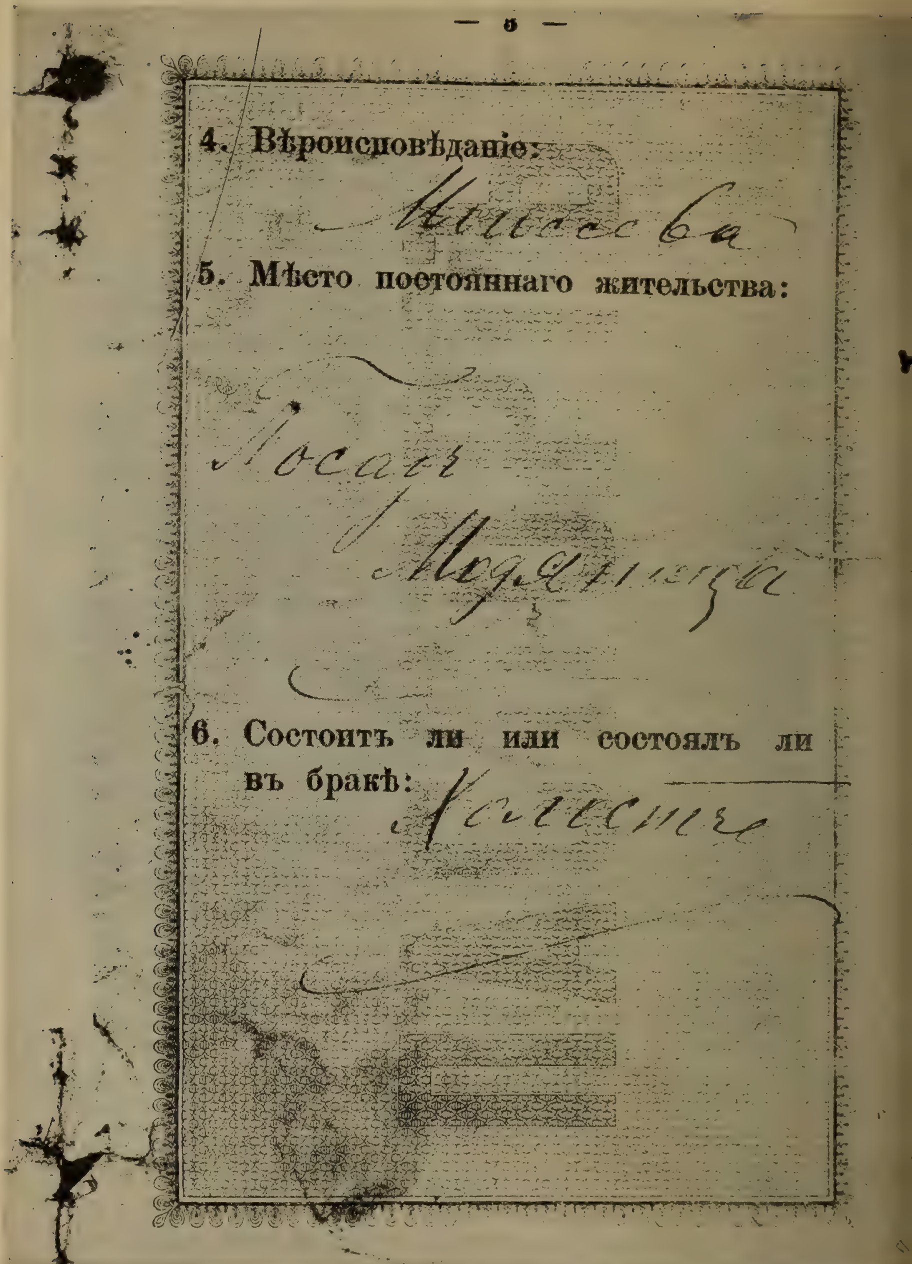
For producing magnified reproductions of documents, if sufficient length of camera-extension is provided, a photographic lens with short focus of the ordinary kind may be used; but where the camera has to be portable or considerable direct enlargement is of advantage, a lens similar to a microscopic objective, but furnished with an iris diaphragm, may be utilized.

Where likeness of form is to be demonstrated, photomicrographs (see figs. 17 and 18) may be obtained with such lenses, and these pictures may be very useful, but it does not do to generalize from one or two points. In identifying a handwriting there must be a sufficient number to satisfy the examiner that they are not due to coincidences, and they must also be such peculiarities as are not due to two persons having learnt from the same style of copybook or do not represent racial or family characteristics.

It must be borne in mind that a photograph may be a false witness, or it may be ignorantly if not intentionally misinterpreted. In the case of a document, alterations or additions may have been made after the photograph was taken, or something may have been removed from the latter.

The writer remembers the case of a man who was born of German parents in the United States, and who exhibited in this country a photographic reproduction of his American passport in his window in order to give the impression that he was an American citizen. As a matter of fact he was not, for never in the course of many years had he recrossed the Atlantic, and after the copy had been made his passport had been cancelled—with a perforating stamp.

Again, as has been demonstrated by the present writer, it is possible to produce a photograph of a document which really never existed, though the writing represented upon it and the signatures purporting to have been attached are taken from perfectly genuine



— 5 —

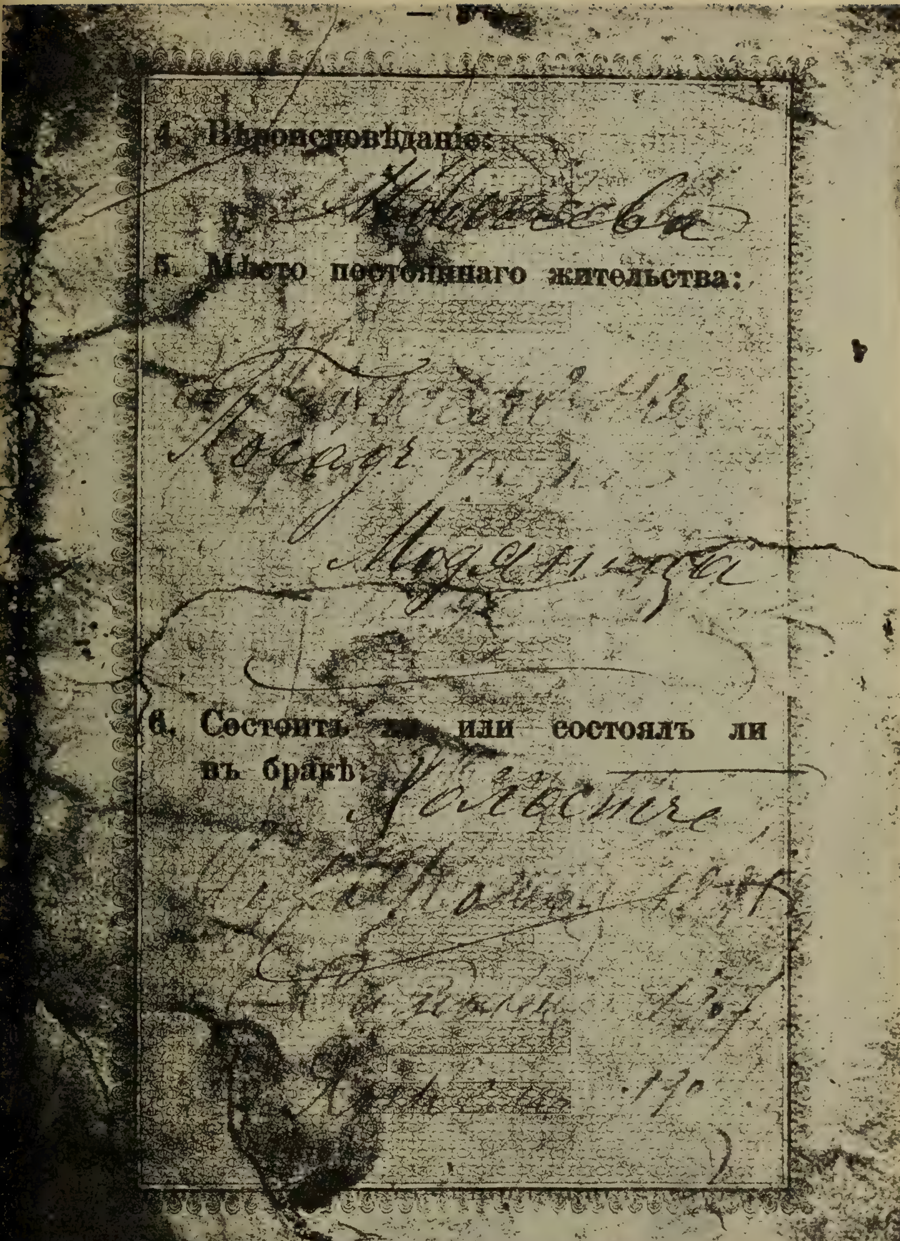
4. Вѣроисповѣданіе: Моисеева

5. Мѣсто постояннаго жительства:

6. Состоитъ ли или состоялъ ли въ бракѣ: Холостъ

Fig. 12.—A page of a doubtful passport before treatment

(By the courtesy of *The Whitchall Gazette*)



4. Вѣроисповѣданіе:

5. Мѣсто постояннаго жительства:

6. Состоитъ ли или состоялъ ли въ бракѣ:

Fig. 13.—The same page showing three other series of entries which were brought up, and which proved that it had been used by four different people

(By the courtesy of *The Whitehall Gazette*)

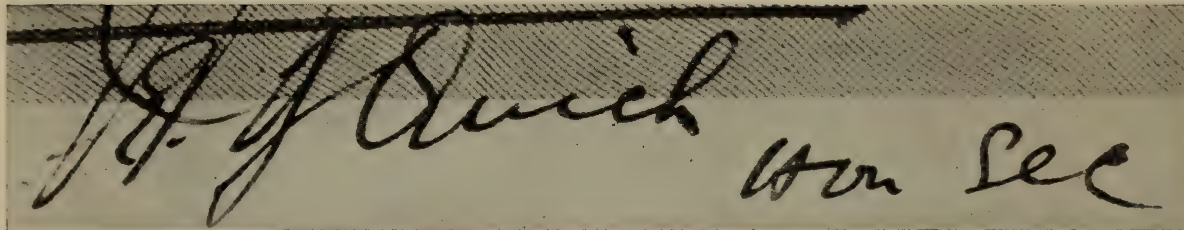


Fig. 14.—A genuine signature on a cheque

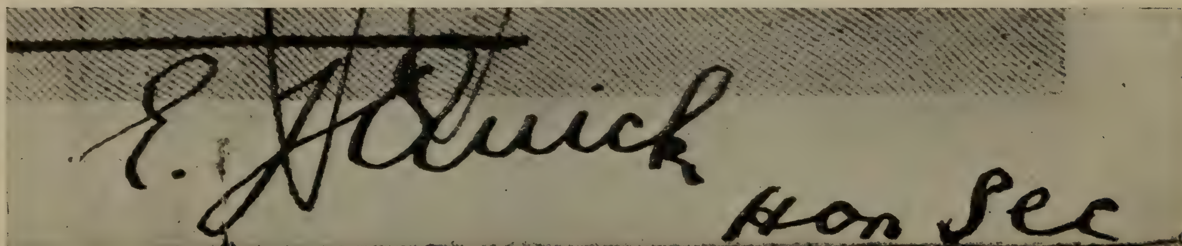


Fig. 15.—A forged signature which has apparently been traced from the one shown in the previous figure

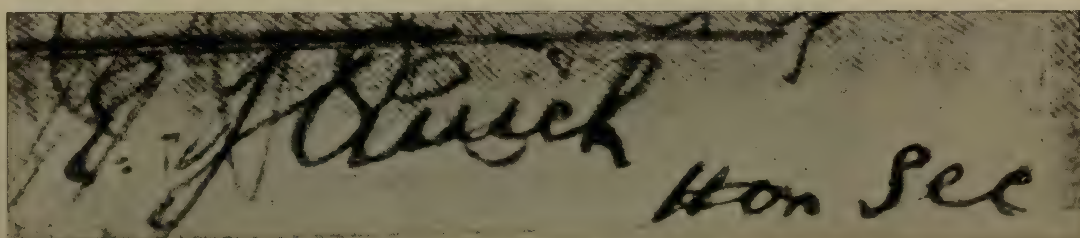


Fig. 16—The two signatures superimposed and photographed with the light behind them, showing how nearly identical they are as regards the position of the strokes composing them and the contractions which follow

Fig. 17.—A photomicrograph of the letter "f" from a disputed document, one of a number of characters picked out for comparison.

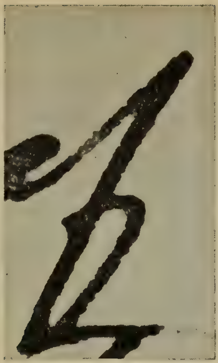


Fig. 18. — The letter "f" from the known writing of the man to whom the one seen in the previous figure was attributed.

Fig. 19.—An ink stroke over typewriting

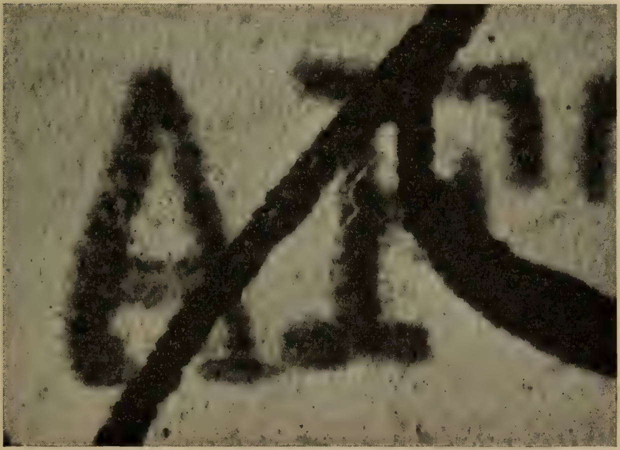


Fig. 20.—Typewriting over ink stroke

originals. The whole thing depends upon the making of a very careful patchwork, and removing from the negative of it all signs of joining.

Anyone who looks at the photomicrograph which is reproduced in fig. 19 would say that the letters " R.E." have been typed over the piece of ink writing which crosses them, and contrariwise that the pen-stroke seen in fig. 20 was superimposed upon the letters "A.F.". The conclusions would, however, be quite wrong, for the reverse is really the case. The specimens were prepared for an experiment, and to avoid, so far as possible, error in comparisons, they were made with the same ribbon and the same ink on pieces of the same paper, and they were photographed on the same plate.

In cases of disputed writing such exhibits, if improperly described, might well have secured wrong verdicts. What may have happened in these instances is that the ink (whether from ribbon or pen) first applied to the paper has not only sunk into the fibres and stained them, but has also changed them so that they are little affected by subsequent writing over the same spots. Hence the first writing, where crossings have taken place at a later period, would come up more strongly in the photograph, and therefore appear to be uppermost.

There is another possible explanation, namely, that in fig. 19 the ink writing has not become really blackened and consequently comes out lighter in tint than the typewriting, and in fig. 20 it has matured more and become darker than the letters made with the ribbon, but further investigations may show that this is not the case.

PLATES

Fig. 2

A, Laminated pearlite and ferrite, × 3000. Zeiss 2-mm. apochromat N.A. 1·40; monochromatic blue light. (Negative × 1000 and enlarged.)

B, Pearlite (finer than in A), × 3000. Watson 2-mm. Holoscopic objective N.A. 1·35; yellow-green light. (Negative × 1400 and enlarged.)

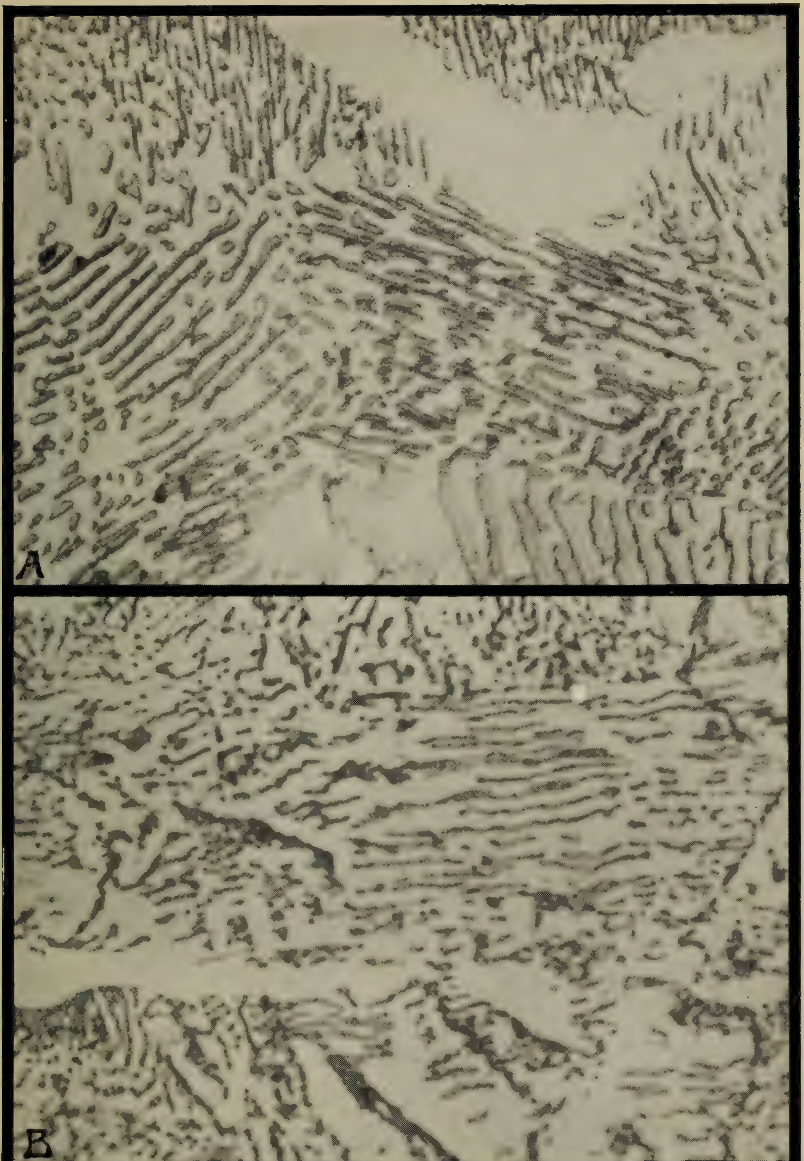

A
B

Fig. 3

A, Eutectic in gun-metal, ×750. Zeiss 4-mm. apochromat N.A. 0·95; process plate, no screen.

B, High-speed steel, etched sodium picrate, ×750. Watson 4-mm. Holoscopic objective N.A. 0·95; allochrome plate, green screen.

C, Carbide in annealed mild steel, ×750. Ross $\frac{1}{8}$-in.; allochrome plate, green screen.

D, Globular pearlite, ×500. Watson 12-mm. Holoscopic objective N.A. 0·65; allochrome plate, yellow screen.

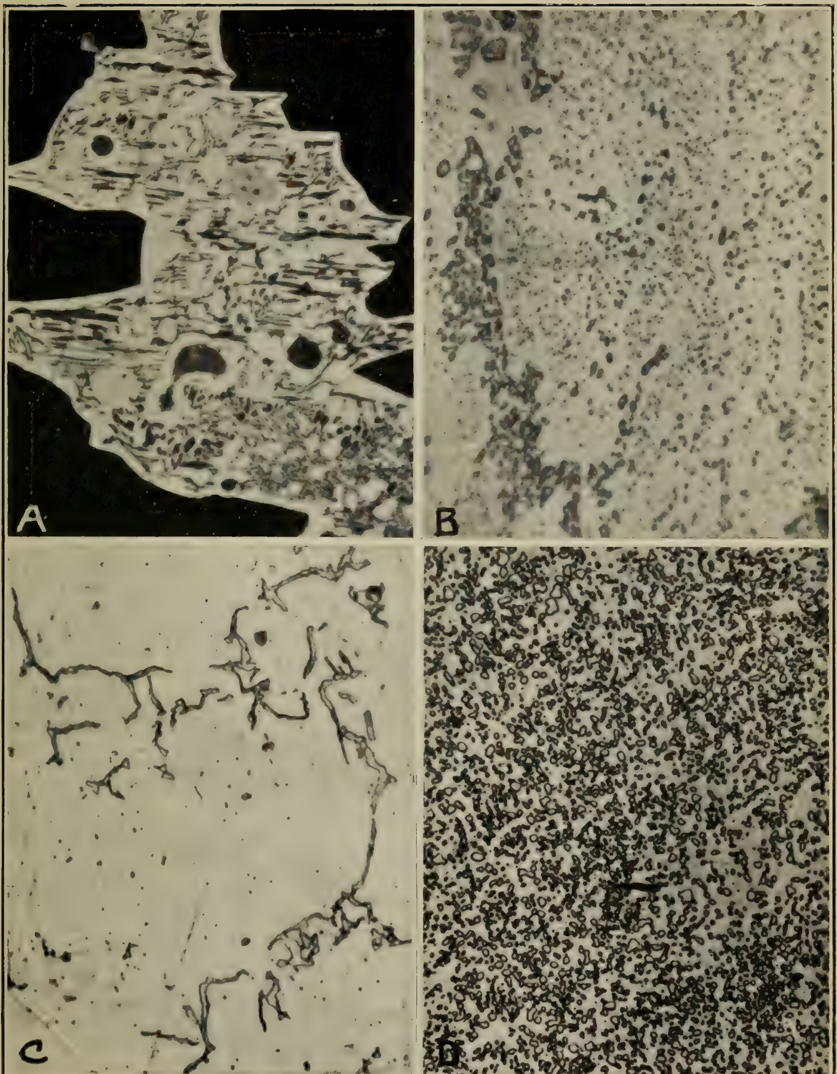

A
B
C
D

Fig. 4

A, Austenite and martensite, × 100. Zeiss 24-mm. apochromat N.A. 0·3; process plate, no screen.

B, Neumann bands (iron silicon alloy), × 100. Watson 24-mm. Holoscopic objective N.A. 0·24; allochrome plate, green screen.

C, White iron eutectic, × 300. Watson 12-mm. Holoscopic objective N.A. 0·65; allochrome plate, green screen.

D, Weld in mild steel, × 100. Swift 1-in. achromat N.A. 0·25; allochrome plate, green screen.

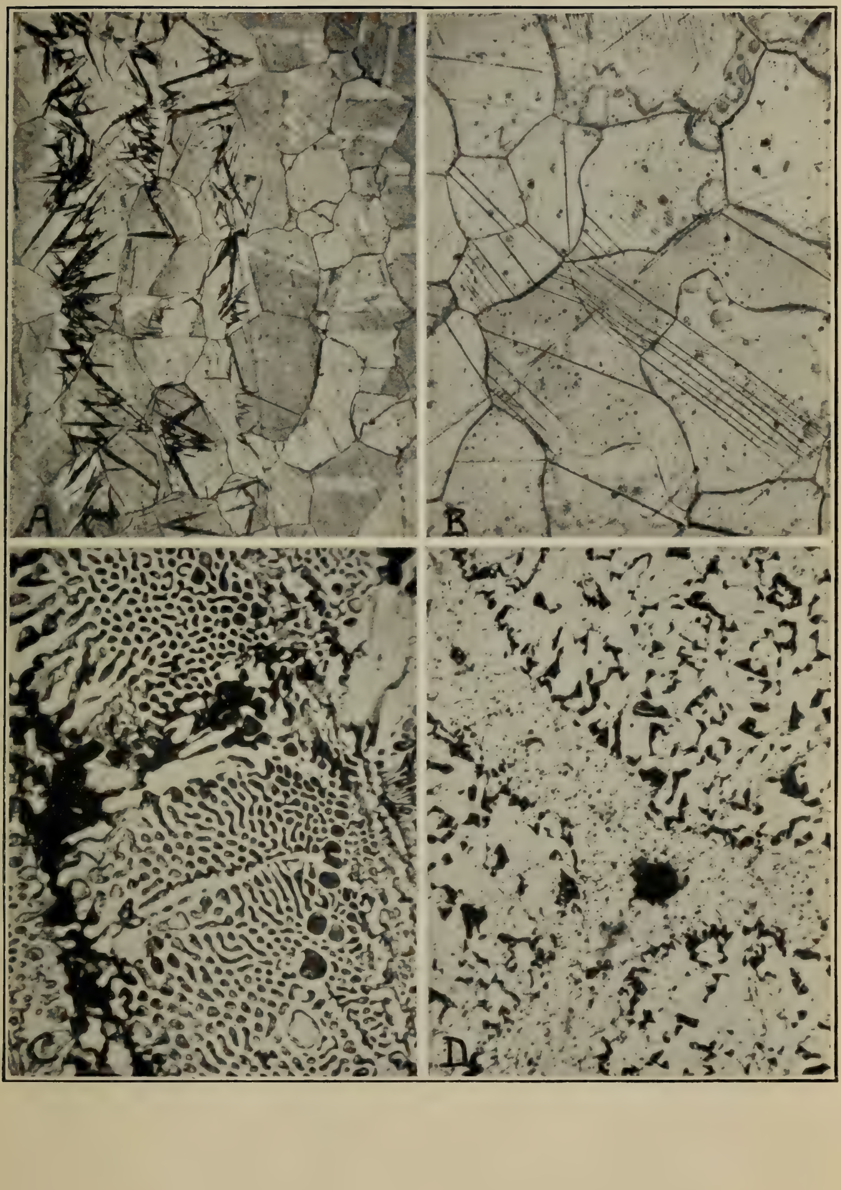


Fig. 5

A, Wrought iron, × 100. Watson $\frac{2}{3}$-in. Parachromatic objective N.A. 0·28.
B, Mild steel casting, × 50. Watson 2-in. N.A. 0·17.
Both allochrome plate and green screen.

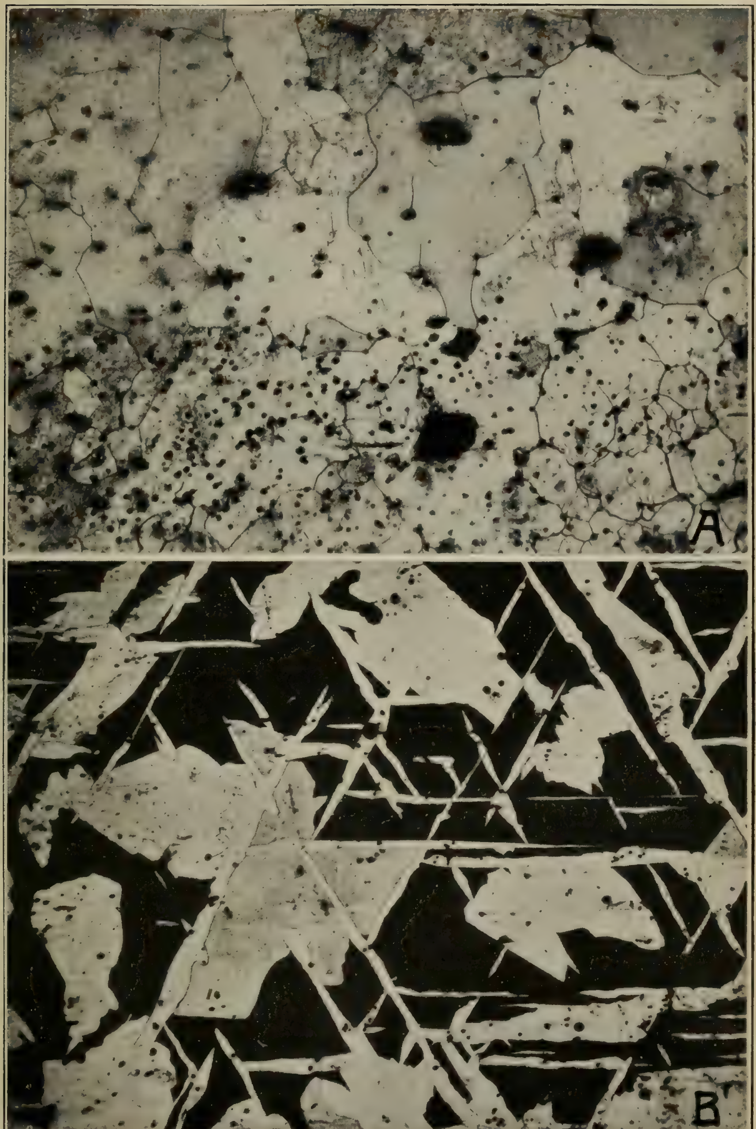

A
B

Fig. 7

Effect of thick disc on low-power objective. Globular pearlite, ×200. Zeiss 24-mm. apochromat N.A. 0·30; monochromatic blue light.

A, Taken with thin disc.

B, Taken with thick disc (see p. 290).

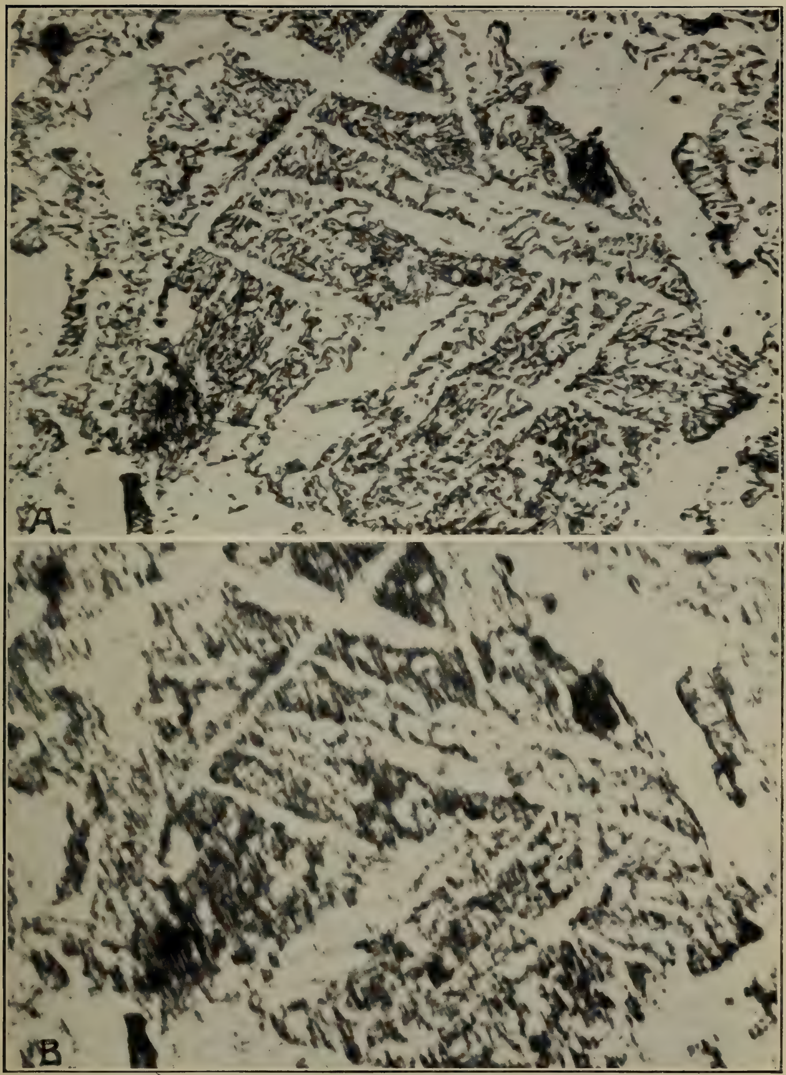

A
B

Fig. 17

Spring Suspension of Photomicroscope to eliminate Effects of Vibration

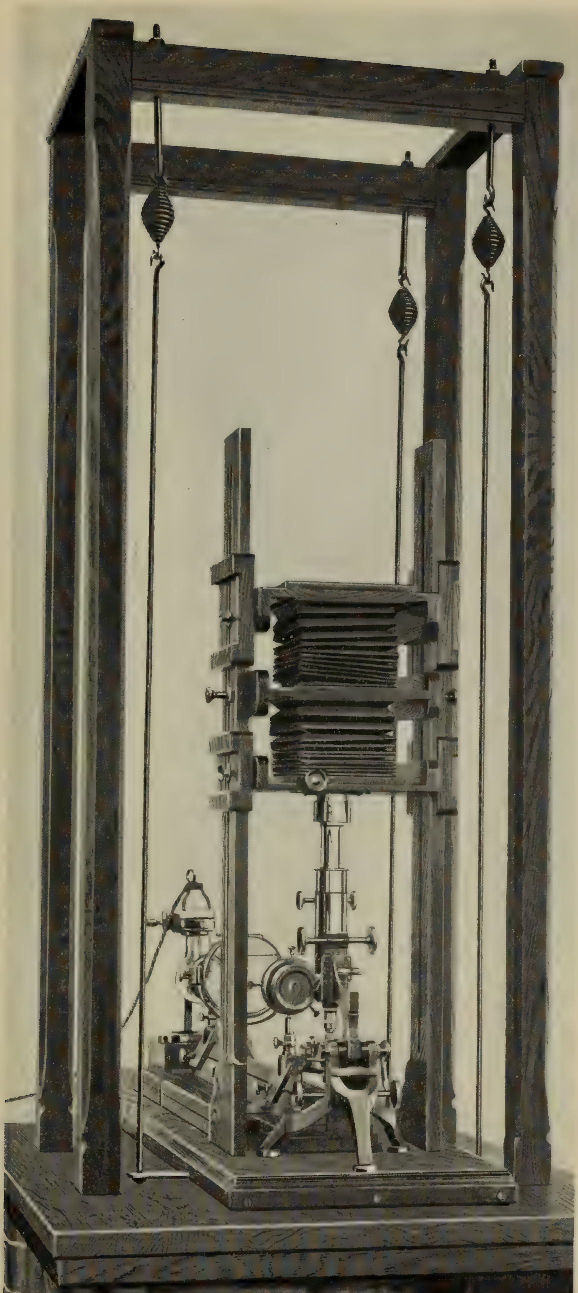


Fig. 19

Microscope and Condenser arranged for Low-power Photomicrography

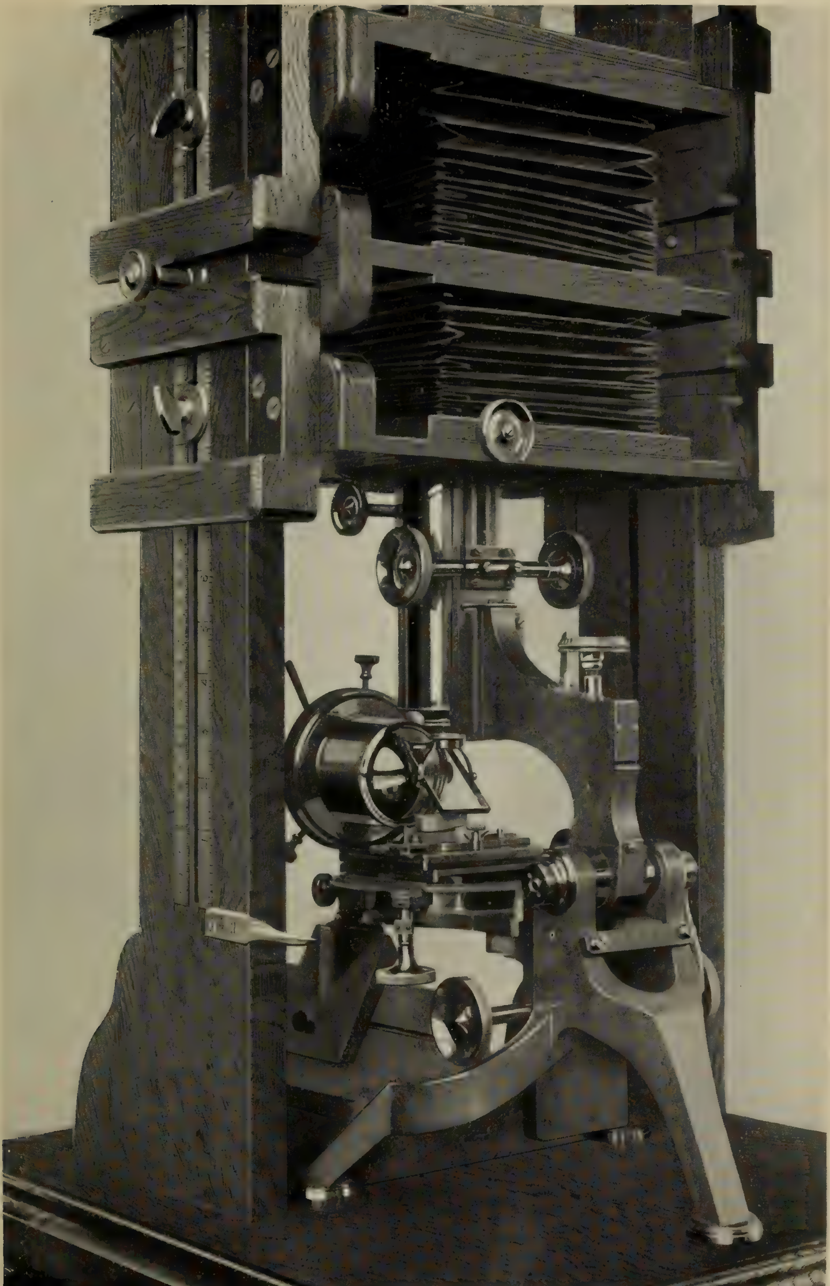


Fig. 20

Burnt steel, × 10. Zeiss 35-mm. projection objective.

Ocular, none.
Plate, Imperial process.
Screen, none.

Condenser system, fig. 18.

Fig. 21

Hot worked Muntz metal, × 40

Objective, Watson 2-in. N.A. 0·17.
Ocular, × 5 Holoscopic.
Plate, Wratten allochrome.
Screen, tricolour green.

Condenser system as described, p. 308.

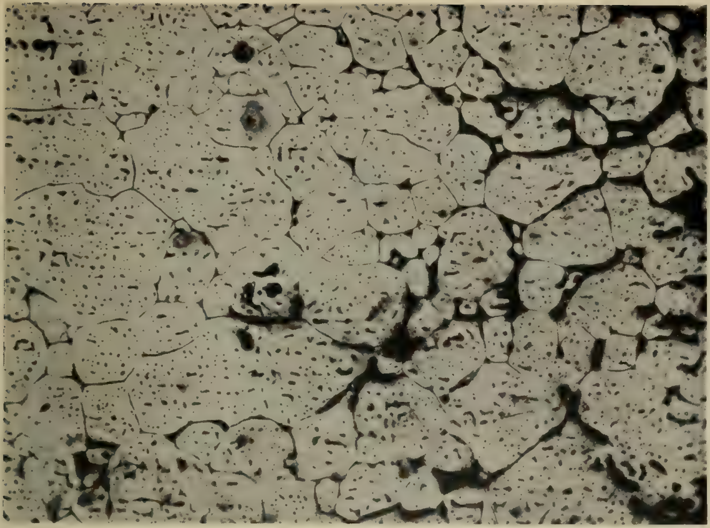
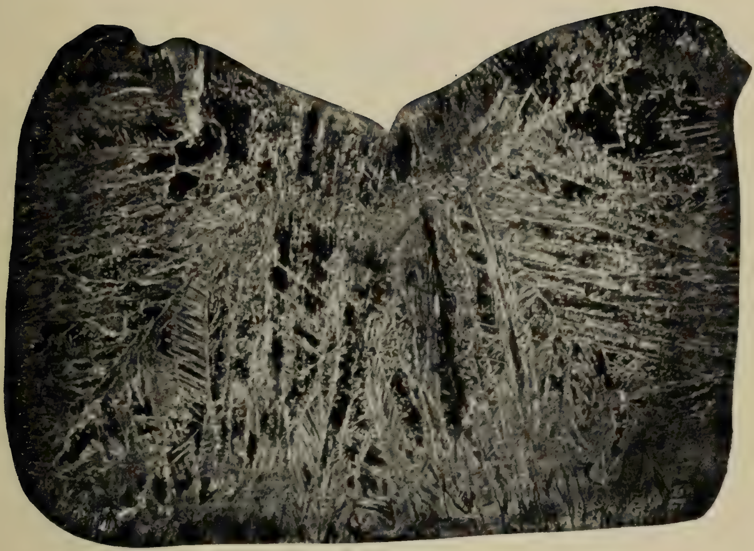


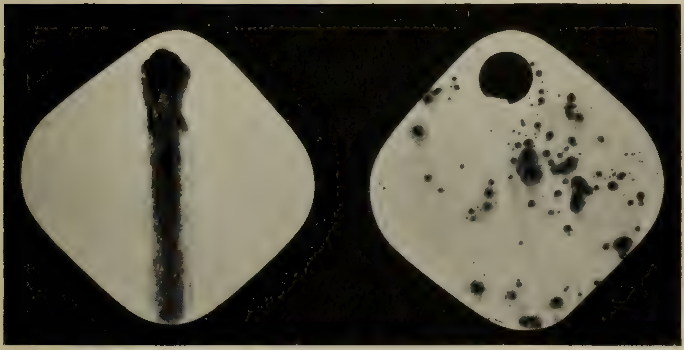
Fig. 23

Chill Crystals in Small Steel Ingot (etched cupric reagent), $\times 4$

Fig. 25

Corroded Steel Discs, actual size, photographed with approximately vertical illumination as described on p. 310





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